STRENGTH PARAMETERS OF SOME BRITTLE DENTAL MATERIALS: WEIBULL STATISTICS.

A Thesis Submitted

By

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To My Children

"No investigations can be called true science without passing mathematical tests" - Leonardo de'vinci

ABSTRACT

There are many factors affecting the mechanical strength of a material. The effects of specimen size and strain rate (crosshead speed of testing) on the compressive, diametral tensile and flexural strengths some of the brittle dental materials are the main factors investigated in this study.

The study was composed of two parts. The first part was to study the effect of specimen size and strain rate (crosshead speed of testing) on the compressive, diametral tensile and flexural strengths of a material tested. Weibull and Normal statistics were used to analyse the data. The analysis showed that specimen size and strain rate (crosshead speed of testing) affect the strength of a brittle materials. The optimum specimen size and crosshead speed of testing were determined for the compressive, diametral tensile and flexural tests. These specimen size and crosshead speed of testing are the 'test parameters'. The analysis also showed that the Weibull statistics was more adaptable method used in assessing the strength of a brittle materials. Therefore the value of Weibull modulus, characteristic strength and a

stress at an arbitrary failure probability of 0.01 percent are the 'strength parameters' concluded from the analysis. In addition the relationship between Weibull modulus and deviation coefficient(%) and the relationship between deviation coefficient(%), mean strength and characteristic strength were established from the results of this investigation. A good correlation coefficient were obtained for these relationships.

In the second parts of the study, 'strength parameters' some of brittle dental materials were determined by using the 'test parameters' found in the first part of the study. In addition the relationships found in the first part of the study were used as a model to estimate the 'strength parameter' from a mean strength and and standard deviation of a small sample (a sample of 5 specimens). The results of this study showed that a stress at an arbitrary failure probability of 0.01 percent for the small sample was not significantly varied from the stress at the same arbitrary failure probability of the large sample size.

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CHAPTER ONE

INTRODUCTION

1.1 General Introduction

It is assumed that the values of strength calculated from mechanical testing follow the Gaussian distribution or Normal distribution equation. The curve of the Normal distribution equation is symmetrical about its centre and has a characteristic bell-shape. The Normal distribution is determined by two parameters: the mean and standard deviation. The standard deviation is a measure of the spread of the probability about the mean value. If the value of the standard deviation is small, the distribution is tightly packed about the mean. When the standard deviation is large the distribution is rather flat and widely spread. By using this method, the reliability of the strength of a material is judged from the mean and the standard deviation. Furthermore a confidence limit is also calculated. The probability that the mean value is contained in the interval is called confidence limit. Normally the 95 percent or 99 percent confidence limit is calculated.

The comparison of two or more means may be analysed by using a statistical method called Analysis of Variance (ANOVA). However the mean and standard deviation may not be the correct parameters for reporting results, particularly for brittle materials. If a graph of probability of failure is plotted against stress for the strength of a material

(Figure 1.1), the true strength is thought to lie on the upper part of the distribution i.e on the dotted part of the curve. The values of stress that have been measured in mechanical tests are found along the curve which are below the true strength. Particularly for brittle materials, the stresses which are below the true strength are caused by flaws.

Mean strength only reflects a percentage failure probability and may be approximated by taking 50 percent of the failure strength of the material. Because the mean value as previously described is a percentage of the failure probability, it cannot be used as a design parameter. This is because the 50 percent failure probability has a very high risk of failure. This may explain why most brittle materials fail at an unpredictable stress below the mean value.

Figure 1.2 represents the results from the mechanical testing of two brittle materials. Material B has a mean strength higher than that of material A, but at stress equal to 180 MPa, material A will perform better because it has a lower probability of failure. This is another reason why the mean strength and standard deviation are not suitable parameters for reporting the strength or the performance of brittle materials. Thus the probability of

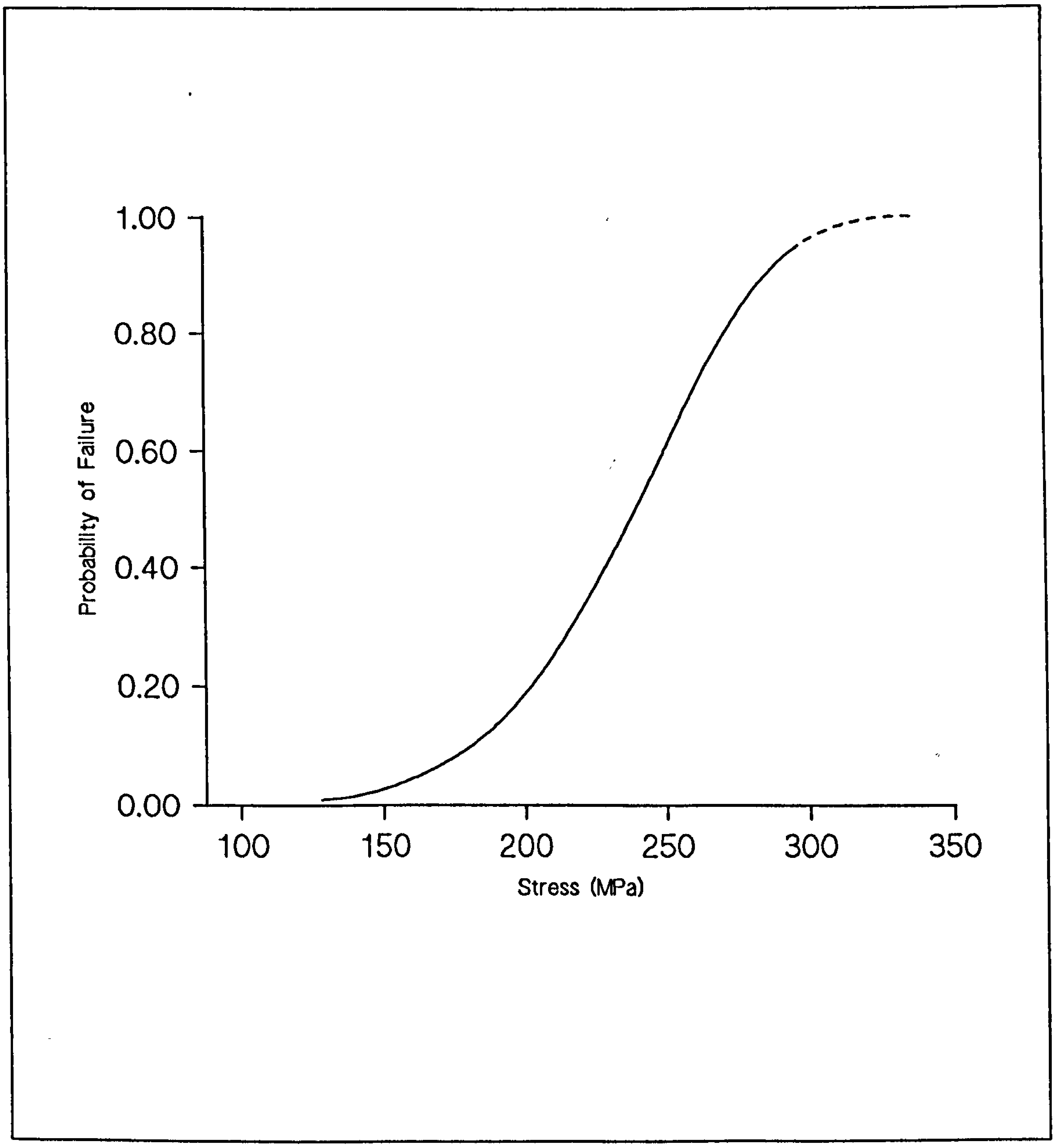

Figure 1.1 - A typical Weibull distribution curve.

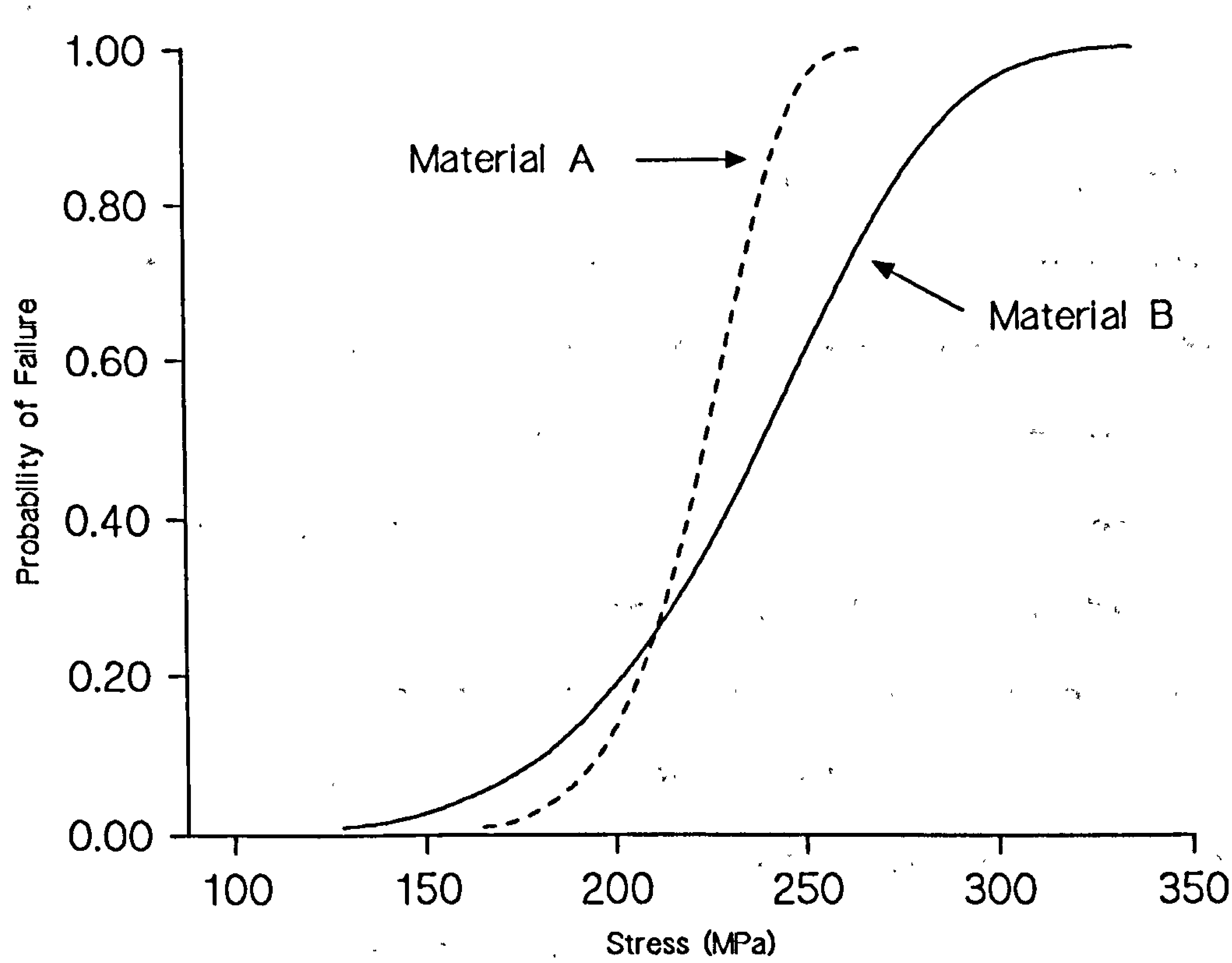

Figure 1.2 - Comparison between the strength of two materials.

failure at any stress level must be predicted. A standardised probability level should be established in order to assess the performance of brittle materials.

1.2 Plan of Work

The investigation was divided into two parts. In the first part of the investigation, tests were conducted to investigate the effect on the compressive strength, diametral tensile strength and flexural strength of a brittle material, of the size of the specimen and the crosshead speed used for testing. (This is because the strengths of brittle materials measured by a mechanical testing machine are found to be influenced mainly by the specimen geometry (Seshadri and Srinivasan:1981, Stanler and Wendt:1987, Price and Murray:1973, Jones et al:1972, Osborn and Skinner:1959) and the crosshead speed of the testing machine (Jayatilaka and Trustrum:1977, Jones et al:1972). All the tests described above were designed to find the most reliable specimen geometry for each test and at which crosshead speed should it be performed. These results were to be used in the second part of the investigation. A batch of thirty specimens were used in each experiment.

In the second part of the investigation, results from part one were taken and another series of compressive, diametral tensile and flexural strength tests were carried out. Six batches of five specimens were tested for each experiment.

The Weibull distribution equation was used to analyse the data. Normal distribution and Student's t-distribution were also used for comparison.

1.3 Scope And Aim Of Investigation

The aim of this investigation was to determine whether the mechanical properties of brittle dental materials can be accurately fitted to a predictive statistic such as a Weibull distribution. In addition, it was also aimed to use this approach to investigate the variables which influence the testing of brittle materials such as specimen geometry, specimen size, ~~age~~ and the strain rate during testing.

The type of mechanical tests under investigation were compressive, diametral tensile and flexural strength tests. The data obtained from the various mechanical tests was analysed by a computer program called `Strength Analysis'. The program is designed for Weibull statistic and Normal statistic. The program listing is shown in appendix A. A sample of 30 specimens were used in each experiment.

The hypotheses of the investigation are

a. Weibull analysis can be used to predict brittleness.

b. Weibull analysis can be used to predict material performance.

c. The Weibull distribution gives a better estimation at extreme ends of the distribution than Normal distribution.

d. The crosshead speed for mechanical testing - can influence strength and must be chosen carefully.

e. The Length/diameter ratio of the compressive and diametral tensile specimen affect the strength of the material.

Other factors to be investigated included:

i. Storage condition may affect the strength of a brittle material.

ii. Mean strength and Coefficient of deviation may be used to estimate the Weibull modulus and characteristic strength.

CHAPTER TWO

~~LITERTURE~~ REVIEWS
LITERATURE

2.1 WEIBULL STATISTIC

2.1.1 Introduction

(McCabe et al: 1990,

Many investigators / McCabe and Carrick:1986, McCabe and Walls:1986, Errington:1979, Davies:1973, Stannley et al:1973, Walls:1986, Kennerley et al:1982, Sivill:1974, Robinson:1967, Kamiya and Kamigaito:1984, Kittl and Aldunate:1983, Jayatilaka and Trustrum:1977, Trustrum and Jayatilaka:1979, Kesshanvan et al:1980, Leon and Kittl:1985, Claudus and Boch:1984, Margetson and Sherwood:1979) have used the distribution known as the Weibull distribution function proposed by Weibull (Weibull:1951) to simulate the scattering results of failure stress. Most of these workers focused on the tensile strength of the material as the Weibull distribution function was originally proposed for the tensile test. McCabe (McCabe and Carrick:1986) showed that the Weibull distribution function also 'fitted' the data from compressive, diametral tensile and flexural strength tests. The data from the compressive and the diametral tensile strength tests was found to have a better 'fit' to the Weibull distribution function than the flexural strength test. The data from the flexural strength test is believed to fit a more complex Weibull equation (Errington:1979, Davies:1973, Stannley et al:1973) involving loading factors , volume and density etc.

2.1.2 Weibull Statistical Basis

If the size of a flaw (Z) in a component of a brittle material is considered, a crack will start propagating from this flaw if the stress (σ) locally exceeds some critical value. According to fracture mechanics and Griffiths theory (Brown and Srawley:1966), stress is a function of the size of the flaws in the material and it is inversely proportional to the square-root of the flaw size. Equation (1) and (2) are ,respectively, taken from fracture mechanics and Griffiths theory.

$$\sigma = \frac{K_{Ic}}{Q\sqrt{(Z)}} \tag{1}$$

where K_{Ic} is the fracture toughness and
Q is a geometrical factor and Z the flaw size.

$$\sigma = \frac{1}{Q}\sqrt{\left[\frac{2E\tau}{Z}\right]} \tag{2}$$

where

τ = the surface energy

E = Young's Modulus and

Q = Geometrical factor

The geometrical factor depends on the shape of the flaw. For a large flaw , it depends on the relationship between specimen size and flaw size (Brown and Strawley:1966).

The parameter K_{Ic} is a material constant particularly for solid homogeneous materials but for some brittle materials, for example Reaction-bonded Silicon Nitride, flaws are very closely spaced and the properties of the material in the neighbourhood of any given flaw are dictated by other flaws. Thus the fracture toughness (k_{IC}) for brittle materials is questionable. In the testing of the fracture toughness, a knowledge of the geometrical factor for a particular test geometry is required. However the geometry of a flaw in a brittle material is difficult to visualise.

2.1.3 Weibull Distribution Equation

Several functions have been considered for the analysis of mechanical test data (Errington:1979) and that proposed by Weibull (Weibull:1951) has been accepted as a fair representation for brittle materials. The original Weibull distribution equation was introduced by Waloddi Weibull (Weibull:1951) and the basic form of the Weibull equation that gives the relationship between the probability of failure (P_f) and the stress (σ) may be written as (McCabe and Carrick:1986):

$$P_f = 1 - \exp\left[- \frac{(\sigma-\sigma_u)}{\sigma_o} \right]^m \qquad (3)$$

where σ_u ,σ_o and m are constant. The three parameters of the above failure probability function, are defined as follows:-

(a) σ_u is known as the threshold stress. It is a constant and denotes the stress at which the failure probability approaches zero. In practice σ_u is usually relatively small when compared to the mean strength and is assumed to be zero by many workers (McCabe and Carrick:1986, McCabe and Walls:1986, Davies:1973, Stannley et al:1973) although for many applications it is not sure whether σ_u is zero or not. It is misleading to overestimate the value of σ_u and as a result σ_u,is taken to be zero.

(b) m is known as the Weibull modulus. The Weibull modulus has an important practical implication. It is a measure of the variability of the quantity $(\sigma-\sigma_u)$. The Weibull modulus, m , has been given a physical meaning by Jayatilaka (Jayatilaka and Trustrum:1977) which characterises the brittleness of the material. A high value of m indicates a close scatter or grouping of the fracture stress data. A wide scatter of data with a long 'tail' at a lower stress levels is reflected by a low value of Weibull modulus.

(c) The last parameter, σ_o, is difficult to visualise and is normally referred to as a 'normalizing parameter' or characteristic strength. When the Weibull modulus is equal to 1 this value is equivalent to the mean value of the normal distribution. As

$$\sigma = \sigma_o\left(\frac{1}{m}!\right)$$

where $\left(\frac{1}{m}!\right)$

is the gamma function and m is the Weibull modulus. The normalizing parameter value is equivalent to the value of 63.21% failure probability when the value of Weibull modulus higher than 1. Later in this text it is called the characteristic strength.

This equation is the most basic equation of the Weibull distribution function. It is widely used in the analysis of the strength data of brittle materials because the probability of the failure for a critical flaw has been found to be closely approximated. The equation is derived using the principle of the "weakest-link hypothesis".

The equation is derived and applied to the analysis of the strength of brittle materials by the following assumptions (Davies:1971 and 1973):

(a) The 'weakest-link hypothesis is applicable'. "Weakest-Link" hypothesis is applied to brittle materials where the brittle component fails when the stress intensity at any flaw in the component reaches the critical value required for the crack to propagate.

(b) Failure cannot occur below zero applied stress.

(c) Failure must occur at a sufficiently large stress.

(d) The number of flaws in the specimen is sufficient to support the "weakest-link" hypothesis.

An alternative parameter which can be used in place of σ_o and has immediate physical significance is the arithmetic mean of the values of failure stress for all the specimens in the sample. It has been shown that

$$\bar{\sigma} = \sigma_o \left(\frac{1}{m} ! \right)$$

where $\left(\frac{1}{m} ! \right)$

is the Gamma function and m is the Weibull modulus. Thus equation (3) may be rewritten as (Stannley et al:1973):

$$P_f = 1 - \exp \left[- \left[\frac{1}{m} ! \right]^m \left[\frac{\bar{\sigma}}{\sigma} \right]^m \right] \qquad (4)$$

This form of the Weibull distribution function, relates the failure probability to the fracture stress and is characterised by the two parameters,Weibull modulus and mean strength. According to Kennerley (Kennerly et al:1982), it is applicable in cases where the applied stresses are uniaxial and uniform. For a complex stress system (for example the diametral tensile test) the form of equation (3) and (4) are unchanged if the fracture stress , σ_f , is taken to be proportional to the fracture load F (i.e σ_f = $2F/\pi Dt$). Where π is the mathematical constant (pi). However it has been shown by McCabe (McCabe and CarricK:1986) that equation (4) was adaptable for all the mechanical tests (i.e compressive, diametral tensile and flexural tests).

Kennerley (Kennerley et al:1982) showed that the variation in density and volume of the specimens affected the value of modulus.It is well established (Stannley et al:1973) that volume variation alone will give rise to variations in the tensile fracture stress. Therefore the value of the Weibull modulus derived from the test data without regard to these variations will be systematically incorrect. A modified Weibull distribution function in which the volume and density dependence of fracture stress are included (Kennerley et al:1982). The derivation of this distribution function is in the appendix of Kennerly (Kennerley et al:1982).It is vital to mention, that this modified equation was designed for non-identical brittle specimens.Even though it is claimed to be suitable for identical specimens, no studies proving its versatility have been documented. In addition this equation is difficult to apply and requires at least 100 specimens.

2.1.4 Estimation of Weibull Parameters

Estimation of the Weibull parameters is not as easy as estimating the mean fracture stress from the experimental data. It is not so straight forward and involves a complex calculation. There are several procedures available as suggested by Robinson (Robinson:1967) and Trustrum (Trustrum and Jayatilaka:1979). But three methods widely used are

(a) a linearization technique by using the " least squares method".

(b) by direct curve fitting using the " least squares method".

(c) by direct curve fitting using the " maximum likelihood " method.

A number of publications (Davies:1973, Sivill:1974, Robinson:1967, Trustrum and Jayatilaka:1979) show various methods of estimating the value of the Weibull modulus but there is no strong evidence that one method is significantly better than the others. It has been pointed out by Trustrum (Trustrum and Jayatilaka:1979) that the specimen size and the 'Failure probability function $P_f(i)$' affect the method of estimation.

Failure probability function $P_f(i)$ is the probability of failure at the i^{th} fracture stress. There are three failure probability equations commonly used.

$$P_f(i) = 1 - \left[\frac{i}{N+1} \right] \tag{5}$$

$$P_f(i) = 1 - \left[\frac{i-\frac{1}{2}}{N} \right] \tag{6}$$

$$P_f(i) = 1 - \left[\frac{i - 0.3}{N + 0.4} \right] \tag{7}$$

where N is the number of specimens in the batch

Failure probability equation (5) is commonly and widely used by several investigators (Trustrum and Jayatilaka:1979, Scott and Gaddipati:1978, Gumbel:1958). Trustrum (Trustrum and Jayatilaka:1979) in his work used failure probability equation (6). Gumbel (Gumbel:1958) used all the failure probability equations described above.

Kamiya and Kamigaito (Kamiya and Kamigaito:1984) had investigated the effect of various failure probability equations on omission of some data in a sample. The omission of 2 to 4 percent of the data, of the highest and the lowest ranked, are most desirable with the survival probability function (6). But it is not sensible to reject any of these data. It causes bias of the sample. To overcome this problem, the failure probability equation (5) is to be used in this study.

2.1.4.1 Estimation of the Threshold Stress, Weibull Modulus and Characteristic Strength.

The threshold stress σ_u has been mentioned in an earlier section of this chapter and is assumed to be equal to zero. Trustrum (Trustrum and Jayatilaka:1979) pointed out that the value of zero has been recognized by many investigators (McCabe and Carrick:1986, McCabe and Walls:1986, Davies:1973, Stannley et al:1973). It had been found that the data gave a close 'fit' for $\sigma_u = 0$ than for other values of σ_u. When the value $\sigma_u=0$ has been assumed, the consistency in the definition of the Weibull Modulus can be made.

Basically the Weibull Modulus (m) is estimated by the following routine:-:

(a) the data of the fracture stress σ_f obtained from the mechanical test are ranked in an ascending order of stress. The weighted rank is given for fracture stresses of the same magnitude.

(b) the failure probability (P_f) corresponding to the i^{th} failure stress is calculated by the failure probability of the equation (5) that has been mentioned earlier.

(c) the corresponding values of the failure probability P_f (i) and fracture stress σ_f are substituted in the equation (3). The value of the Weibull Modulus is obtained by regression analysis. This regression analysis is easily done by using a computer. A program in Fortran language has been written in order to do this task. The program listing is shown in the appendix A.

As mentioned elsewhere in this section, there are three methods of regression that can be used in estimating the Weibull Modulus and characteristic strength of a brittle material. These methods had been compared by Trustrum and Jayatilaka (Trustrum and Jayatilaka:1979) and they found that the linearization technique by using the least squares-method gave the closest fits to the experimental data. Many other investigators (McCabe and Carrick:1986, McCabe and Walls:1986, Errington:1979, Davies:1973, Stannley et al:1973, Walls:1986, Kennerley et al:1982, Sivill:1974, Robinson:1967, Kamiya and Kamigaito:1984, Kittl and Aldunate:1983, Jayatilaka and Trustrum:1977, Trustrum and Jayatilaka:1979, Kesshanvan et al:1980, Leon and Kittl:1985, Margetson and Sherwood:1979) have used the least squares method and claimed that it closely fits the experimental data.

In this technique the Weibull modulus, m , is obtained from the gradient of the $\log_e \log_e(1/1-P_f)$ versus $\log_e(\sigma_f)$ linear plot. The characteristic strength is indirectly obtained from the intercept of the linear plot with $\log_e(\sigma_f)$ axes (i.e characteristic strength is equal to the exponential of the intercept value).

2.1.5 Specimens Number and Methods

In designing an experiment to find the Weibull Modulus , m , of brittle materials , the investigators have to decide how many specimens are to be used. The error of the estimate is inversely proportional to the square root of sample size ,N. So the number must be increased by a factor of four to decrease the standard error by half. Trustrum and Jayatilaka (Trustrum and Jayatilaka:1979) suggested that the least square method needs a sample size of about forty when the failure probability equation (6) is used. With the same equation, for a sample size of less than forty but over twenty, the "maximum likelihood" method gave the smallest standard error.

McCabe and Walls (McCabe and Walls:1986) suggested that a meaning full result can be achieved when at least thirty or more specimens are used. The correlation coefficient is higher when cumulative groups of specimens of around sixty to seventy in number are used (McCabe and Carrick:1986). This indicates an improving 'fit' is achieved when a large number of specimens are used.

Kamiya and Kamigaito (Kamiya and Kamigaito:1984) found that, at least forty or more specimens are required to give the estimated value of Weibull Modulus close to the ' true ' value of Weibull modulus, m. This finding agrees well with the work of Trustrum and Jayatilaka (Trustrum and Jayatilaka:1979).

2.2 NORMAL STATISTIC

A normal distribution is a ~~continous~~ continuous probability function. Figure 2.1 shows an example of the normal frequency distribution curve. It is symmetrical about the middle and exhibit a shape like a bell which is peak in the middle and gradually falling-off at both sides.

The probability density, f(x), of a normally distributed random variable, x, is given by expression shown in equation (8) (Armitage:1971)

$$f(x) = \frac{1}{\sqrt{2\pi}} \exp\left[-\frac{(x-X)^2}{2s^2}\right] \qquad (8)$$

where X is the expectation or mean value of x. The mean value is a summation of raw value, x, divide by a total number of sample size. "π" is the mathematical constant 3.14159 (to 5 decimal points). "s" is a standard deviation of x and can be calculated by the expression below.

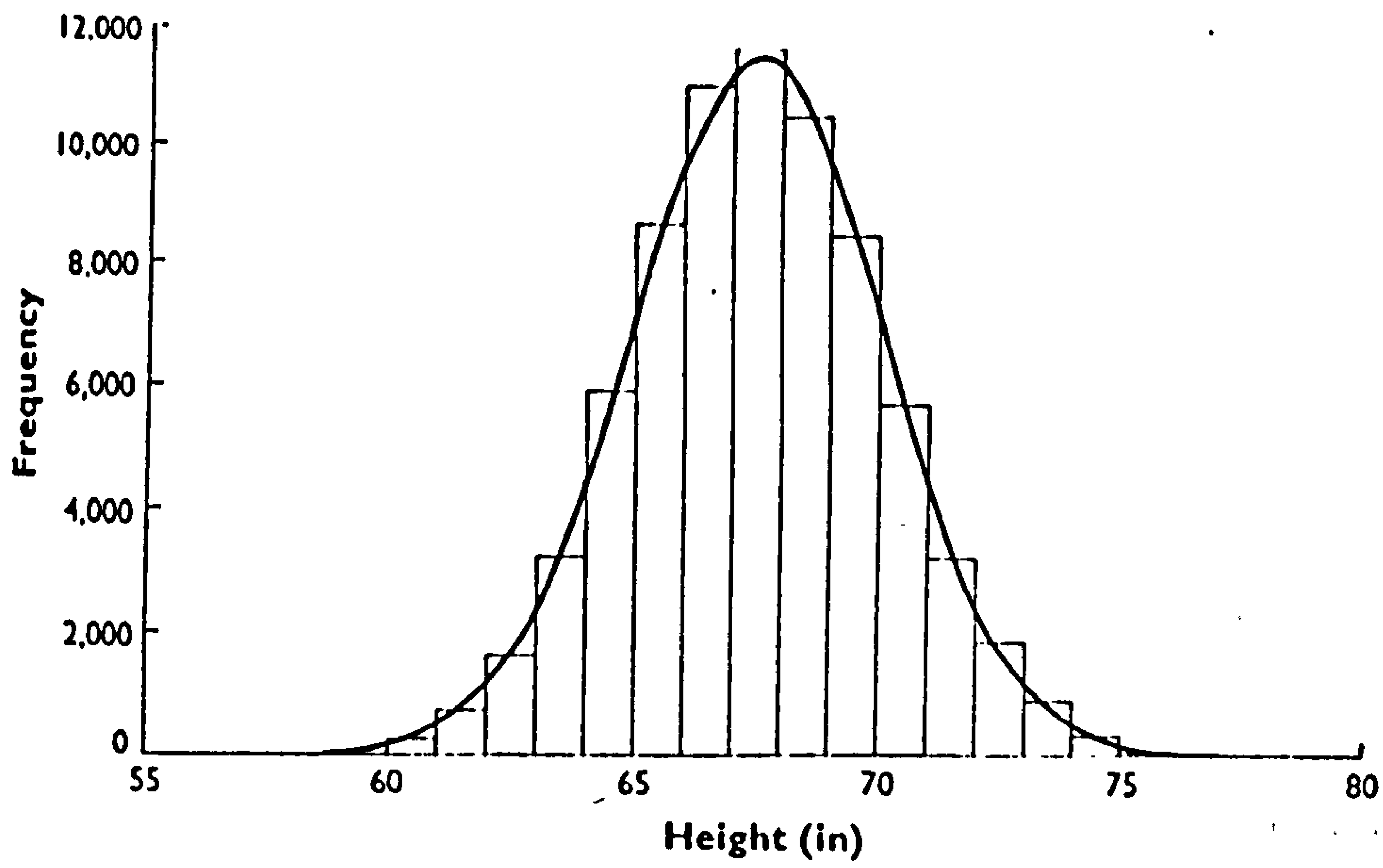

Figure 2.1 A distribution of heights of young adult males. Extracted from Figure 2.10 of Statistical Methods in Medical Research by P. Armitage. Blackwell Scientific Publications.

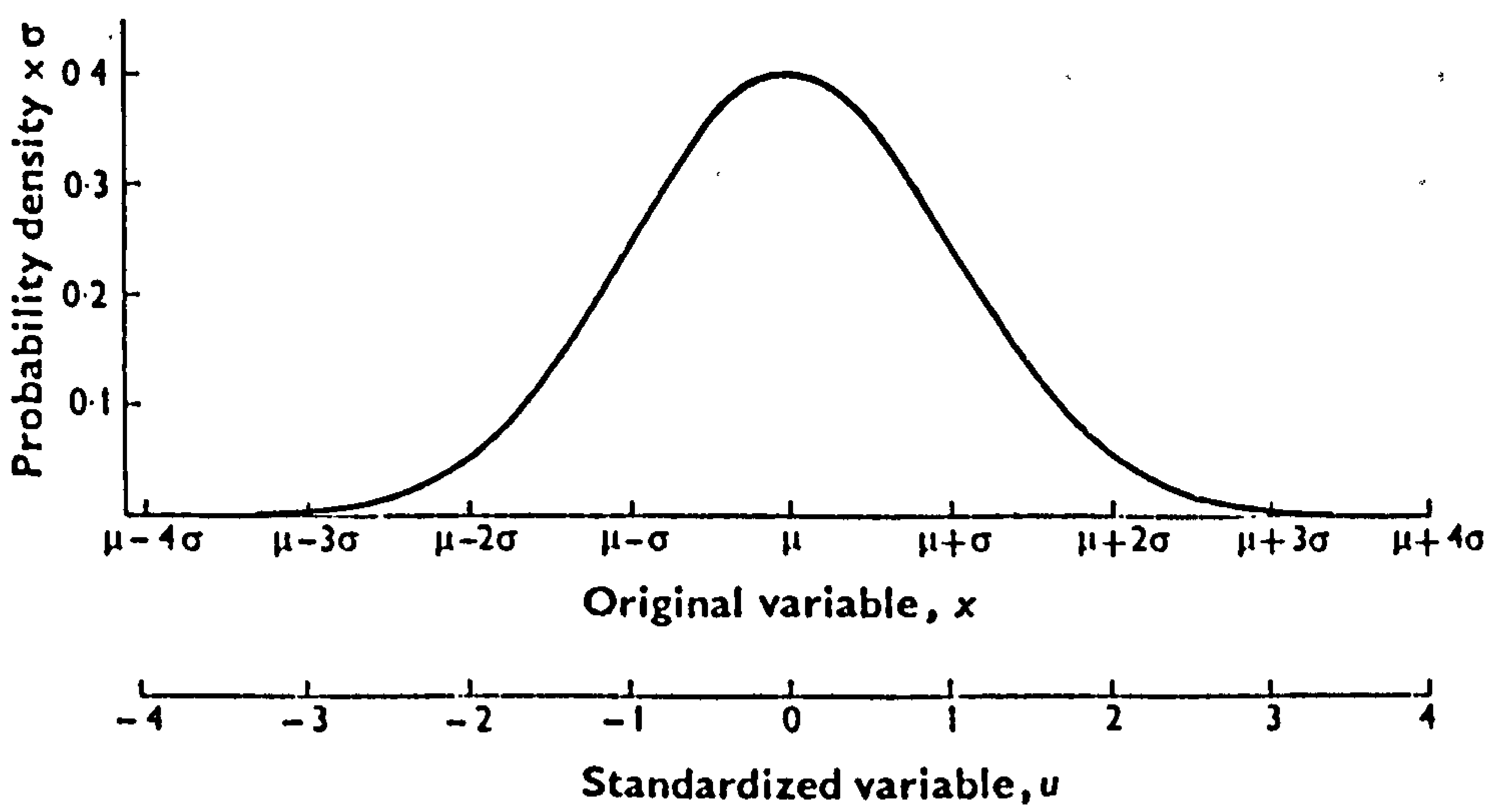

Figure 2.2 The probability density function of a normal distribution showing the scales of the original variable and the standardized variable. Extracted from Figure 2.12 of Statistical Methods in Medical Research by P. Armitage. Blackwell Scientific Publications.

$$s = \sqrt{\left[\frac{(\Sigma x_i - X)^2}{N}\right]} \qquad (9)$$

Figure 2.2 shows the curve of the equation (8) when plotted on the horizontal axis which marked the positions of the mean and the values of x which differ from mean, X, by ±s, ±2s, ±3s and so on. A relatively small proportion of the area under the curve lies outside the ~~the~~ pair of values x = X+2s and x = X-2s. These area is about 5 percent of the total area (Armitage:1971). In term of probability that x lies outside this range is 0·05 . Therefore it might thought any probabilities would have to calculated for every pair of values of X and s but this is not so as the probabilities depend on the expression of the departure of x from X as a multiple of s as shown on the lower scale of the Figure 2.2 (i.e the multiples of ±1, ±2, ±3 and so on). The probabilities under various parts of any normal distribution can be therefore expressed in terms of the standard deviate. It can be calculated by using the equation 10 below.

$$u = (X-x)/s\sqrt{N} \qquad (10)$$

Where "u" is a normal standardized deviate. "X" is a mean value of x and "s" is a standard deviation of x (Equation 9). "N" is a total number of a sample.

Some important results are shown in the Table 2.1. More detailed results are given in Table A of the appendix D.

Table 2.1 - Some probabilities associated with the Normal distribution.

Some probabilities associated with the Normal distribution		
Standardized deviate	Probability of greater deviation	
	In either direction	In one direction
0.0	1.000	0.5
1.0	0.317	0.159
2.0	0.046	0.023
3.0	0.0027	0.0013
1.645	0.1	0.05
1.960	0.05	0.025
2.576	0.01	0.005

* Extracted from Table 2.5 of the Statistical Methods in Medical Research by P. Armitage:Blackwell Scientific Publication 1971.

For the 95 percent confident limit, the raw value must be in the range of X ± 1.96s. And for the 99 percent confidence limit the raw value must be in the range X ± 2.576s. In other words, the standardized deviate must be greater than 1.96 ~~1.096~~ for the raw value to be significant at the 5 percent level. And the value of standardized deviate must be greater than 2.576 ~~2.76~~ for the raw value to be significant at the 1 percent level.

The above equation (10) is normally used for the testing of sample sizes of more than 30 specimens. For the smaller sample i.e N is less than 30, the confidence interval is widened to allow for the error in estimating the standard deviation and then equation 11 is used. The standardized deviate is replaced by corresponding values from Student's t distribution. The t value varies with sample size N.

$$t = (X-x)/s\sqrt{N} \tag{11}$$

The 95 and 99 percent confident intervals are $X \pm t_{(n-1/0.05)}(s/\sqrt{N})$ and $X \pm t_{(n-1/0.01)}(s/\sqrt{N})$ respectively. The value of "t" , calculated for the raw value at probability p must be greater than the tabulated value of $t_{n-1/p}$ .The tabulated value of $t_{n-1/p}$ is shown in the Table B of the Appendix.

2.3 Type of Mechanical Testing

2.3.1 Introduction

Literature on the determination of the mechanical properties of brittle materials, indicates the majority of measurements have been limited to compressive strength. Stress analysis in dental structures supports the hypothesis that restorative materials often fail in tension (Mahler and Terkla :1958). Even though compressive strength is an important property in many applications, tensile strength is more relevant to restorative materials such as Amalgam, Porcelain, Composite Resin etc because these materials exhibit brittle behaviour. Earnshaw and Smith have argued that tensile strength is more important and that it has a more meaningful application for the restorative brittle materials (Earnshaw and Smith:1966).

One traditional method of assessing the mechanical strength of materials is a crushing test or compressive test. This test reflects the measurement of compressive strength. The measurement of the tensile strength of restorative materials may be achieved by the conventional method of uniaxial extension of standard "Dumb-Bell" shaped specimens. This test is a simple procedure when the test specimens may be easily prepared by machining of the material or by introducing the material into a suitably shaped mould before it hardens if it is fluid.

The conventional method of assessing the strength using "dumb-bell" shaped specimens may, however, not be appropriate for brittle materials. This is due to the influence of an uncontrolled testing variables on the strength of the brittle materials. Two of the most important variables encountered are the specimen grip eccentricity and surface stress concentrations, arising from damage at the point of contact. For brittle materials, the effect of unsymmetrical displacements in the contact zone between the specimen and the grip is perhaps the most important barrier to achieve uniform stress fields. The resultant bending moment at the ends of the specimen may significantly lower the value of the ultimate tensile strength (Rudnick et al:1963). In the case of ductile materials, however, the bending moment may be "corrected" by plastic flow in the appropriate region without significantly affecting the ultimate tensile strength. The second variable is the surface damage at the contact zone shown by photo-elastic stress analysis. This results in a stress concentration which may cause the specimen to fail at the grips rather than in the gauge length. The validity of the failure of the specimen at the grips is debatable because the photo-elastic studies by Bortz (Bortz:1963) on brittle polymeric materials indicated that the results were not sufficiently sensitive.

The other method employed for the determination of the tensile strength of brittle materials is the flexural or bending test. Many investigators (McCabe and Carrick:1986, Mitchell:1961, Rudnick et al:1963, Hodson:1959, Jones et al:1972, Shervlin and Lindenthal:1959, Mario and Dickson:1962, Mahler and Mitchem:1964) used this method to measure the flexural strength which is thought to be closely related to tensile strength. The disadvantage of this method is that, when a strip or bar of specimen is bent under the pressure of a three or four point loading system, the distribution of stress is not uniform. The stress distribution in the loaded section varying from zero at the neutral axis to a maximum at the outer convex surface. This is said to accentuate the effect of the surface condition on the measured strength.

A flexural strength or so-called Modulus of rupture can be calculated from the load obtained at failure (Rudnick, Hunter , Holden:1963). Failure is initiated on the surface of the specimen in tension because the maximum stress is concentrated here. It is reasonable to assume that the flexural strength is an approximation of the tensile strength.

Furthermore, from the principles of strength of the materials, a linear stress distribution is assumed in derivation of the formula for flexural strength. The stress distribution of the flexural test is not uniform (Mitchell:1961). Consequently it is not surprising to note that the values of 'tensile strength' obtained in the flexural test are frequently higher by a factor of two or more than those obtained by the conventional method. This has been verified for Concrete (Wright:1955), Porcelain (Bettany ,Webb:1922, Riddle ,Land:1922) and cast iron (Lissel, Itzel:1954).

The occurrence of failure at the surface of the specimens, suggests that quite large discrepancies could arise as a result of the modification of the surface texture. Experiments on glazed and unglazed Porcelain have shown that a layer of glaze of one-eigth of the specimen thickness is sufficient to increase the bending strength by sixty percent (Riddle, Land:1922).

The variability associated with the existing method for establishing tensile strength data caused the investigations of Bettany and Webb (Bettany, Webb:1922) to be concentrated on the development of a simple test for brittle materials, capable of producing acceptable values of tensile strength. One of the results was the development of the diametral tensile test (Williams:1967). The use of the diametral tensile test on solid discs has produced an indirect tensile strength measurement. This method is now well established and has been utilized for the testing of Dental Plaster, dental refractories and brittle materials (Mitchell:1961, Wright:1955, Hundros:1958, Olzar, Kayfasz, Pietrzykowski :1957, Jones:1962, Earnshaw, Smith:1966). Berenbaum and Brodie (Berenbaum, Brodie:1959) used the diametral tensile test to measure the tensile strength of Gypsum Plaster.

2.3.2 Compressive Test

2.3.2.1 Theoretical Studies

The formation of a complex stress system in a cylindrical specimen when loaded with a compressive force is illustrated in Figure 2.3. Theoretically, when the compressive force is applied to each end of the specimen, it resolves into a shear stress acting at a certain angle ß from the vertical plane. Three dimensionally it forms a wedge shape or cone from each end. If the length of the specimen is long enough, tensile stress is formed in the middle of the specimen as the result of the shear force. If the length of the specimen is very short, a more complex stress distribution is formed as a result of overlapping of the wedges or cones. Thus a suitable specimen size is required to obtain reproducible and meaningful test results.

Certain characteristics of the compressive test are similar to those of the tensile test (Robert:1985). The shape of the stress strain curve is similar when recorded in tension or compression. It is possible to approximate the material's modulus of elasticity from this stress-strain curve. The gradient of the curve is the modulus of elasticity. The modulus calculated from the tensile strength test curve is however the best estimation. The elastic modulus is sometime referred to as "Young's Modulus" (Dorn,Tietz:1950).

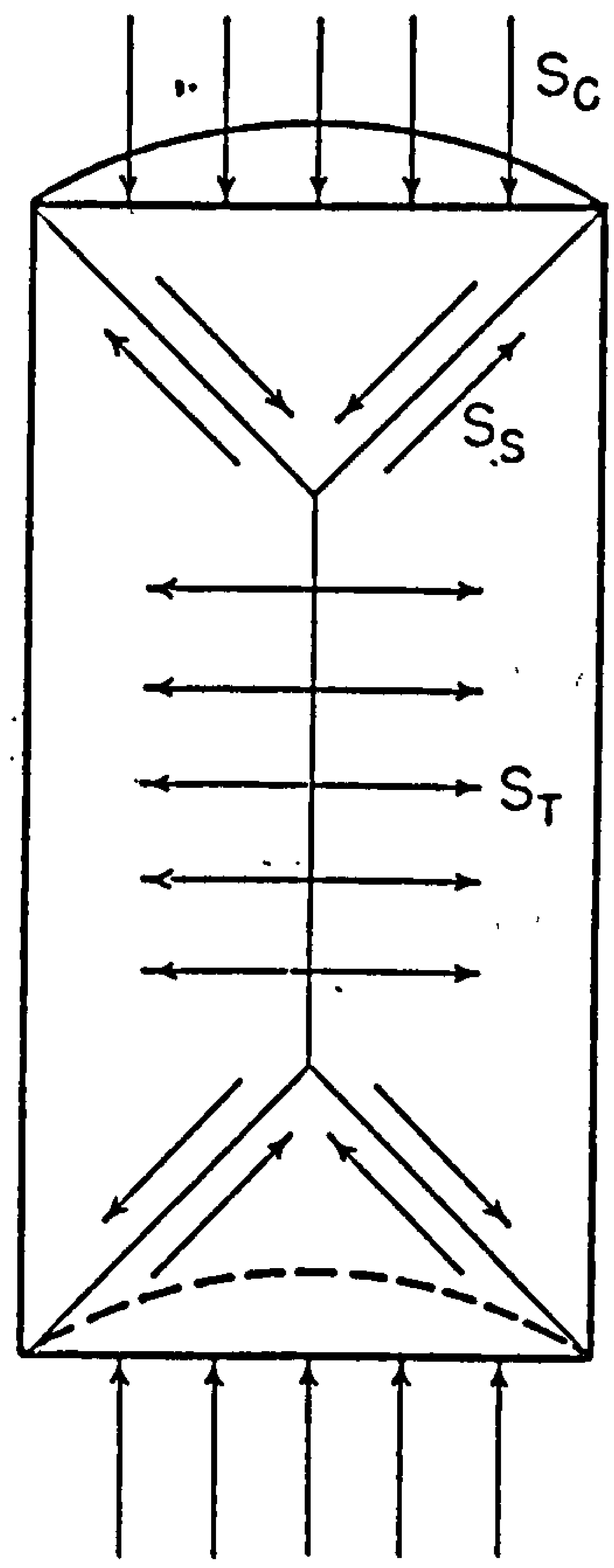

Figure 2.3 Drawing of complex stress pattern developed in cylinder subjected to compressive stress. Extracted from Figure 3.11 of Restorative dental materials edited by Robert G. Craig and Floyd A. Peyton. The C.V Mosby Company - Fifth edition.

The compressive strength of a material is simply calculated from the equation 12.

$$\text{Compressive strength} = \frac{\text{Force (P)}}{\text{Area (A)}} \qquad (12)$$

Where P is the external force applied that cause the specimen to fracture and A is the original cross sectional area of the specimen. Some materials when subjected to compressive force, tend to increase in area. This is evident in some amalgam specimens, if the compressive stress applied to it is less than the stress required for fracture. This quality is one of the properties of amalgam and is it known as "flow" or "Creep". This property will not be discussed here.

2.3.2.2 Specimen Size

The length of a cylindrical specimen should be twice the diameter (Robert:1985). Some of the investigators used a specimen size of diameter/depth ratio 1:2. The specimen sizes of 4 mm diameter by 8 mm depth, 3 mm diameter by 6 mm depth were commonly used. Specimens of 6 mm in length by 4 mm diameter are used in many standards. All the specimen sizes mentioned above are to be analysed in this investigation.

2.3.3 The Diametral Tensile Test

The diametral tensile test was originally known as the Brazilian test. It was named after the people of south America, where it was first introduced to solve engineering problems. The test is widely used to determine the tensile strength of materials such as Concrete (Mitchell:1961 ,Hundros:1958, Olzak, Kayfasz, Pietrzykowski:1957), Ceramics (Rudnick, Hunter, Holden:1963), Amalgam and Cements (Eden, Wateratrat:1965, Sweeney, Burns:1965), Rock (Jones:1962) and Gypsum products (Earnshaw, Smith:1966, Berenbaum, Brodie:1959).

2.3.3.1 Theoretical Studies

The diametral tensile test may be defined as the state of stress developed when a cylindrical specimen is subjected to concentrated forces at it circumference. The stress distribution in the specimen has been studied by various workers (Timoshenko, Goodier:1951, Frocht:1948, Muskhelishvila:1953, Sokolnikoff:1956, Peltier:1954). They stated that the stress distribution in the specimen is dependent on the loading system , whether it is a "line loading" or a "distributed loading".

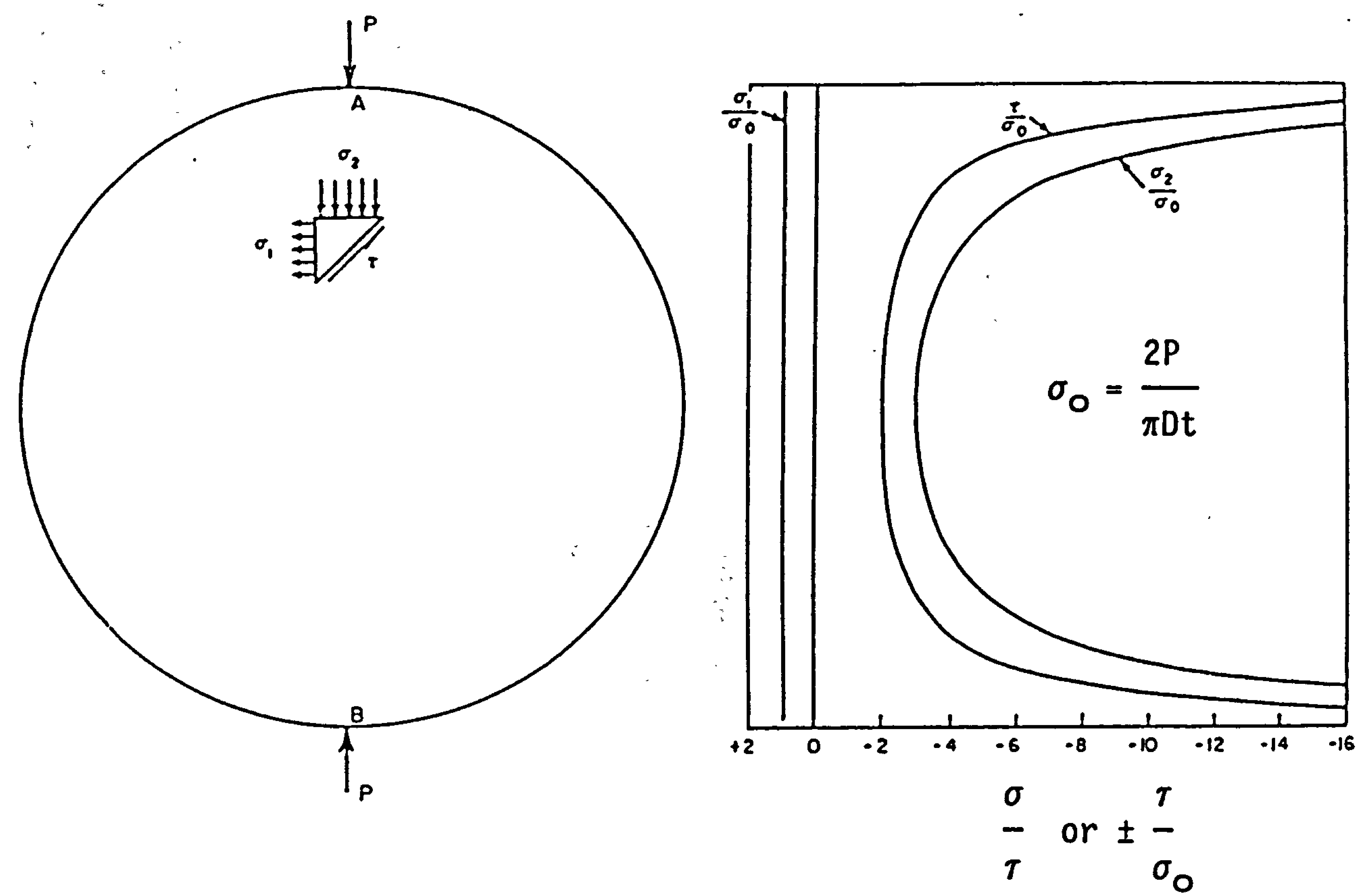

Figure 2.4 Stress distribution across loaded diameter of a disc type specimen compressed between two line loads. After Rudnick, Hunter and Folden:1963.

2.3.3.1.1 Line Loading

Line loading produces a biaxial stress distribution (Figure 2.4) within the specimen and the stresses at any point may be calculated from elastic theory (Peltier:1954). The stress of primary interest is the maximum tensile stress, which acts across the loaded diameter A-B. The magnitude of this stress (σ) is derived from elastic theory (Peltier:1954) and is shown in equation 13.

$$\sigma = \frac{2P}{\pi Dt} \tag{13}$$

where

P is the external force applied,

D is the diameter of the specimen,

t is the specimen thickness and

π is the mathematical constant.

The test may yield valid results if fracture of the specimen is initiated by tensile stress. In addition to tensile stress, a compressive stress is also present which acts along the loaded diameter. Its magnitude varies from the centre of the specimen to the loaded area. The minimum compressive stress at the centre may be of $6P/\pi Dt$ (Peltier:1954) to infinitely higher stress under the loaded area. However Rudnick et al (Rudnick, Hunter, Holden:1963) have shown that tensile stress is the source of crack propagation and thus causes tensile failure in all materials.

2.3.3.1.2 Distributed Loading

A more realistic representation of the test system is achieved when the system is loaded with a distributed loading as any real loading fixture will distribute the load over an area. The self-weight of the specimen is negligible when compared to the applied load. The stress distribution (Figure 2.5) of this system is identical to the plane deformation of a cylinder.

It has also been shown that point loads or short distributed loads applied to the circular element, develop identical stresses at the centre of the specimen (Wright:1955) when the strip width 'a' is less than or equal to 1/12 of the specimen diameter.

2.3.3.1.3 Technique Utilized for the Application of a Distributed Load.

The basic requirement of the tensile test is that the fracture must be caused by tensile stress rather than shear or compressive stress. The most important factors that affect the resultant loading are the elastic modulus of the specimen and the "platens". The effect of the "platens" condition has been investigated (Mitchell:1961, Rudnick, Hunter, Honden :1963, Wright:1955, Robert:1985). Providing that the elastic modulus of the specimens and "platens" are known then the correct loading distribution may be easily obtained by choosing the appropriate "platen" material. A

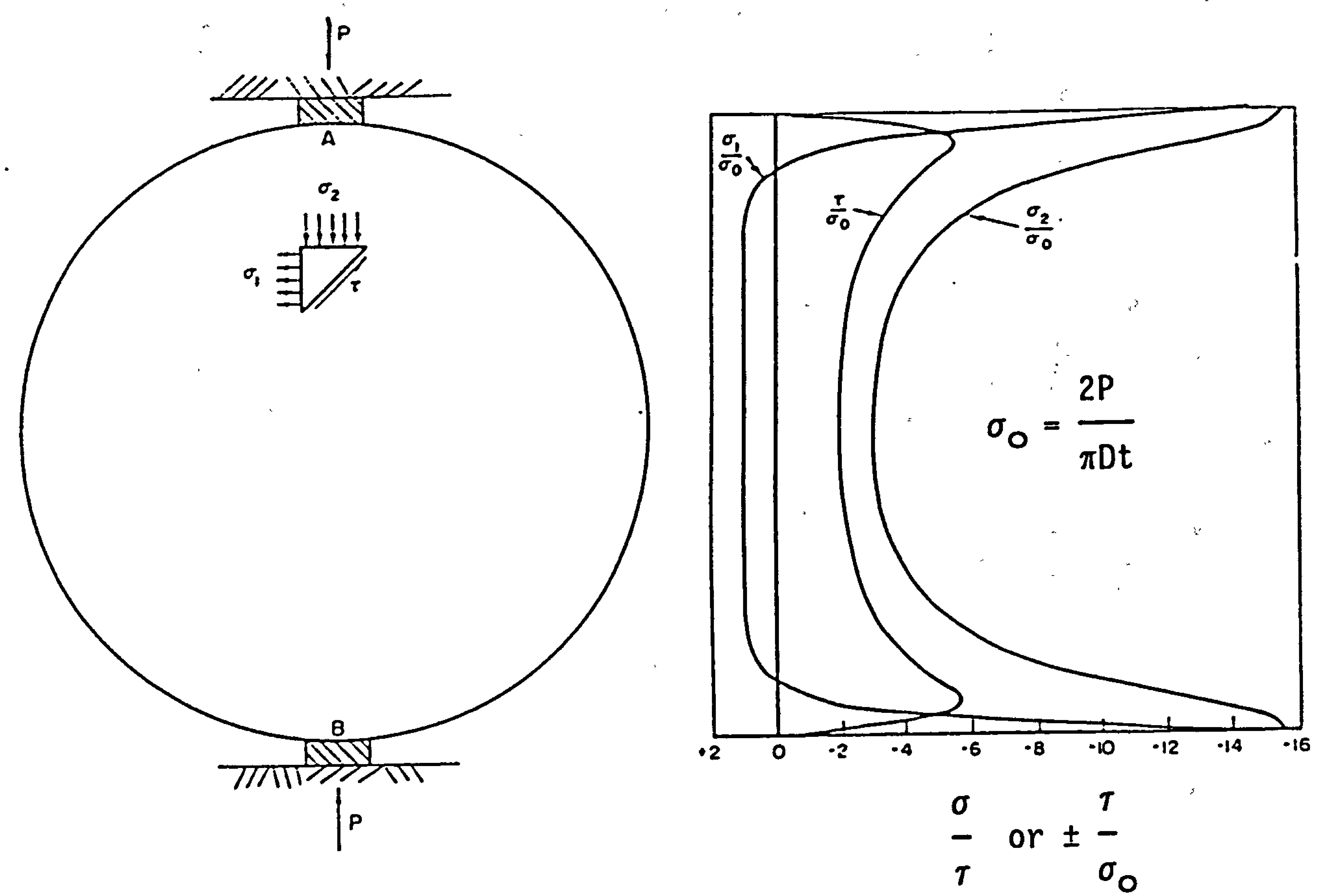

Figure 2.5 Stress distribution across loaded diameter of a disc type specimen compressed between deformable plates. After Rudnick, Hunter and Folden:1963.

variety of thin pads produced from materials such as araldite, cardboard, blotting paper and rubber have been used as "platen" materials. It has been found by several workers (Mitchell:1961, Rudnick, Hunter, Honden F.C:1963, Wright P:1955, Robert G.C:1985) that the effects of load distribution are as follow:

(a) it reduces the effect of surface irregularities and promotes a uniform distribution of applied load along the specimen diameter.

(b) it reduces the maximum compressive and shear stress.

(c) it causes the maximum stress acting across the loaded diameter to depart from uniform tension in the region under load.

The range of tensile strength obtained and the mean strength, increase when using platens of elastic modulus greater than that of the specimen. Stainless steel is suitable to be used as a platen in this investigation because it elastic modulus is greater than that of the restorative materials that will be tested.

2.3.3.2 Specimen Size

The specimen size used by one investigator is different from that used by others. From the literature, the diametral tensile test specimens that are commonly used, can be divided into 3 major geometrical shapes;

(a) A cylindrical type. The diameter/length ratio of is specimens at least 1:2

(b) A solid disc. The diameter/length ratio of the specimens is less than 1:1.

(c) A hollow solid disc or ring disc. This type of test specimen is the same as (b) except there is a small hole in the centre.

In this investigation, specimen geometries of type (a) and (b) were considered. Specimens from type (c) are not suitable for diametral compressive test ~~as has been already mentioned~~ (Williams:1967).

2.3.4 Transverse Test

The flexural test is also known as the three-point bend test and is the test where by a rectangular beam specimen is placed between two supports and then a point load is applied at the middle between the supports. The flexural strength is often described as the modulus of rupture. The flexural strength is significantly useful especially when denture base materials are being compared. In a long span bridge where the biting stress may be severe, the flexural strength of the material is more important than the diametral tensile or compressive strength.

2.3.4.1 Theoretical Studies

The modulus of rupture for a simple beam can be calculated from the equation 14.

$$\text{Modulus of rupture} = \frac{3Pl}{2bd^2} \tag{14}$$

where P is the applied load, l is the length between supports, b is the width and d is the specimen thickness.

The stress distribution in a simple beam test can be determined by the photo-elastic method (Figure 2.6(A)). The isochromatic fringes are illustrated in Figure 2.6(B). It can be seen from the Figures 2.6(A) and 2.6(B) that the beam is in compression above the neutral axis and in tension below the axis. The fracture is initiated in the region which is in tension. If the surface texture of the specimen is poor, the crack may be propagated from a surface flaw either in the tension or compression region.

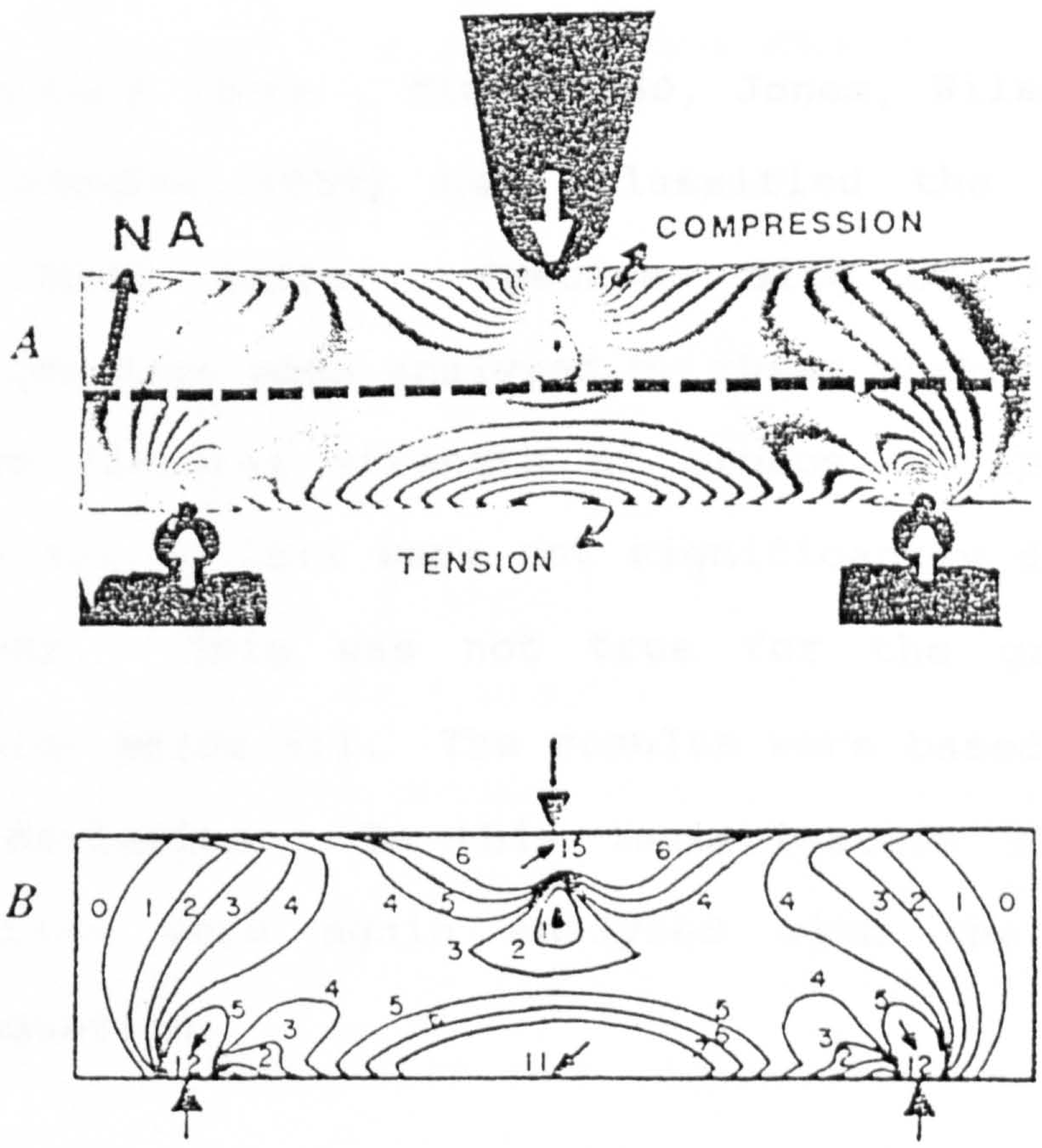

Figure 2.6 Analysis of transverse bending.
A - Photo elastic model with isochromatic fringes.
B - Drawing to illustrate isochromatic fringe order.
Extracted from Figure 3.19 of Restorative dental materials edited by Robert G. Craig and Floyd A. Peyton. The C.V Mosby Company - Fifth edition.

2.3.4.2 Specimen Size

The type of specimen used for the flexural test is a rectangular beam of a square cross section (for example 2 mm by 2 mm by 30 mm in length). Other sizes configurations also have been used. Other than size one can have different support distances or spans.

Some of the workers (Dorn , Tietz:1950, Jones, Wilson:1972, Shervlin , Lindenthal:1959) have classified the specimen size by span/depth ratio. Specimen size of different span/depth ratios have been analysed by these workers. They found that the flexural strength of groups of span/depth ratios between 5:1 to 15:1 were not significantly different from each other. This was not true for the groups of span/depth ratios below 5:1. The results were based on mean and standard deviation. In this investigation all these span/depth ratios were again analysed with the Weibull distribution equation.

2.4 THE EFFECT OF VARIABLES ON MECHANICAL STRENGTH

The strength measured by a mechanical test may be influenced by the specimens geometry, methods of mechanical testing and condition of testing. This is true for the brittle materials. It is important to establish a standard specification so that the variation of results can be monitored and studied in more a efficient manner.

2.4.1 Specimen Size

The selection of specimen size depends on the cost of the material, the time involved, the ease of manipulation, an attempt to create the clinical situation etc. Many investigators (Reports of councils and bureaus:1961, Osborne, Skinner:1959) have pointed out that the size of the specimen may affect the strength of brittle materials. Beside size ; the shape of the specimen may also affect the results. This is evident when the compressive strength of cube and cylinder specimens are compared. The recommended Australian Standard Specification (Australian Standard Association:1963 T:22) stated that the compressive strength determination of dental casting investments for gold alloys, for example, a cube specimen of 25 mm sides should be used. Osborne and Skinner (Osborne, Skinner:1959) used cylindrical specimens of 14 mm in length by 25 mm diameter. This specimen size is according to a modified form of the American Dental Specification (Reports of councils and bureaus:1961). compressive strength can be calculated by a simple formula i.e simply a division of applied force by the an area covered by the applied force.

However this comparison may not be true because the strengths of different specimen geometries have been compared. No investigation has found how compressive strength is affected by the specimen geometry. Brittle materials are more sensitive to this effect than ductile materials. Comparatively little work has been carried out to determine the effect of specimen size on tensile strength. However some workers (Jones, Wilson:1972, Shervlin, Lindenthal:1959, Dorn, Tietz:1950) found that for the flexural test, the geometries of the specimens affects the flexural strength. Some workers (Jones, Wilson:1972, Shervlin, Lindenthal:1959, Dorn, Tietz:1950) pointed out that flexural strength is not significantly different if a cross section of specimen 2 mm by 2 mm is used in the range of span/depth ratios between of 5:1 to 15:1

The determination of tensile strength using the diametral test has been shown to give more reliable results (Williams:1967). However the size and geometry of the test specimen seems to have an effect on the strength values. Seshadri (Seshadri, Srinivasan:1981) used "ring" specimens but others (Stanler, Wendt:1987, Price, Murray:1973) used solid cylindrical specimens. Williams (Williams:1967) has made comparison between solid disc and "ring" disc specimens and finally used solid disc in his experiment to determine the diametral tensile strength. The length/diameter ratio of 1:1 was used. He showed that solid disc specimens were suitable for use in the diametral test.

2.4.2 Rate of Loading

The effect of loading rate (i.e the cross-head speed of tester) on test specimens dictates the mode of failure. With a "slow" strain rate , even brittle materials may show a little plastic deformation before fracture. For a "real" brittle material, the plastic deformation at failure may not occur. A slow cross head speed of 0.1 to 1.0 mm per minute has been used by many workers (McCabe and Carrick:1986, Mitchell:1961, Rudnick, Hunter, Honden:1963, HODSON:1959, Jones, Jones, Wilson:1972, Shervlin, Lindenthal:1959).

Jones (Jones:1962:) studied the variations in rate of loading upon plastic and ceramic materials and stated that at room temperature, the flexural strength increased when the rate of loading was increased. Evans (Evans:1942) studied the effect of the rate of loading upon compressive strength of concrete. The results for various mixes indicated no definite increase in compressive strength for an increase in loading rate up to a certain value. But for faster speeds there was marked increase in compressive strength. The compressive strength of poorly mixed concrete also increased as the loading speed increased.

Jones (Jones:1962) and Evans (Evans:1942) observed, the compressive strength of brittle materials increased by about 33 percent when the time of loading was reduced from 4 hours to 1 second. The effect of increasing the strain rate on specimens of constant diameter, may increase the strength of brittle materials. This may be because there will be less time for stress relaxation at flaws, when a large load is applied over a short period, rather than a longer period. Hence, the application of a fast strain rate may produce failure in a shorter time and at higher load. Jones et al (Jones ,Jones ,Wilson :1972) have pointed out that the strength of dental porcelain increases as strain rate increase. Other studies by Mitchell (Mitchell:1961) have also indicated that an increase in strain rate on concrete specimens produces a significant increase in tensile strength. This variation in results has proved that the rate of loading affects the strength of the material.

2.4.3 Surface Texture

It was stated earlier that an advantage of the diametral tensile test over the other forms of tensile testing is that the maximum tensile stress developed in the specimen is not developed at the surface. If the failure of the flexural specimens is initiated at the surface, the flexural strength calculated from equation 14 is no longer valid. The formula for the "notched" specimen must be used instead. However the notch specimen is used to determined the toughness of the material.

2.4.4 Porosity

Porosity is one of the properties some of brittle materials which affects the mechanical strength. Non-porous brittle materials, for example glass, flaws may affect their strength. The effect of this "property" on the materials strength is discussed under the section of the material itself.

2.5 MATERIALS UNDER INVESTIGATION

2.5.1 Plaster of Paris

2.5.1.1 Introduction

Dental Plaster or Plaster of Paris is one of the gypsum products. The name "Plaster of Paris" was given to this product because it was obtained by burning the gypsum mineral deposits near Paris. Gypsum deposits, however are found in most countries.

Plaster of Paris is obtained from the gypsum mineral, Calcium Sulphate dihydrate $CaSO_4 2H_2O$. The process of driving off part of water of crystallisation is the main event that distinguishes Plaster of Paris from other forms of gypsum products.

$$\text{GYPSUM} \xrightarrow[\text{other means}]{\text{heated or}} \text{GYPSUM PRODUCTS + WATER}$$

Like an ordinary building Plaster, Plaster of Paris is produced when the gypsum mineral is heated in an open furnace at the temperature of about 110^{o} C to 120 ^{o}C (McCabe:1985). This produces a product called Beta-Calcium Sulphate hemihydrate. It is porous and has an irregular shape crystal (Robert :1985).

On heating, dihydrated gypsum in the form of calcium sulphate $CaSO_4.2H_2O$, loses 1.5 gram moles of its 2 gram mole of water of crystallization and converted to Calcium Sulphate hemihydrate $(CaSO_4)_2.H_2O)$ (Robert:1985). When Calcium Sulphate hemihydrate is mixed with water, the reverse reaction takes place. This reaction is exothermic and 3.9 Kilo Calories of heat are developed for every 1 gram mole of Calcium Sulphate hemihydrate reacted (Robert G.C:1985).

Dental Plaster and other gypsum products are mixed with water to produce a workable mix. Dental Plaster usually requires about 45 ml of water for each 100 gram of powder to be properly mixed and produce a workable consistency (Robert :1985). Theoretically only 18.6 percent of 45 ml of water will react with 100 grams of powder (McCabe:1985). The excess water will not take part in the chemical reaction and it exists as free water in the set mass. Usually for every 100 grams of powder, 50 mls of water are used. A mixture of water/powder (W/P) in the ratio of 1:2 will produce a thinner mix which can be easily poured into the mould (McCabe:1985). When dental plaster is mixed with a lesser amount of water, the mixed mass is thicker and this causes difficulty in handling and air bubbles are easily trapped when the mixture is poured into the mould, as a result it produces porous and brittle product, when it sets. This may lead to a lower mechanical strength. It had been shown that different in W/P ratios produce different porosity in the set gypsum and may result different in strength (Robert :1985).

2.5.1.2 Mechanical Properties of Plaster of Paris

Some of the important properties of gypsum products that have a direct effect on the mechanical strength are setting time, size of powder particles, hardness, and setting expansion. The property requirements can be found in American Dental Association (A.D.A), specification no: 25.

It is essential that the consistency of the mixed mass should be constant if the mechanical properties of the dental plaster or the other gypsum products are to be tested and compared. The test for the consistency of impression plaster is called the slump test, 100 grams of plaster are mixed with water and poured into a metallic cylinder mould. After a specific time, the mould is removed and the mixed mass is allowed to spread over the glass slab. By changing the WP ratio,the diameter of the slump mass on the glass is changed. The WP ratio which gives of corresponding to the diameter of the slump mass of 90 ± 3 mm is taken. This is the range allowed by the ADA specification no: 25. The consistencies of model plaster and other gypsum products are measured by a cone penetration test using the Vicat apparatus. The procedures are described in the same specification as stated above.

The compressive strength of the dental plaster and other gypsum products is inversely related to the water/powder ratio, WP, of the mix. If a lot of water is used in the mix, the compressive strength of the set mix is low. As mentioned previously, the dental plaster has the highest quantity of excess water than other gypsum products. It is expected that the compressive strength is lower than others. One hour compressive strength values for dental plaster are reported to be of the an order of 12.5 MPa. There are also mentioned the dry and wet strength of dental plaster. The dry strength is the strength of the gypsum products when all of its excess water is driven out. Whereas the wet strength means the strength of the gypsum products which is the excess water is not completely driven out. It takes approximately 7 days for an average denture flask filled with gypsum materials to lose it excess water. There is no appreciable change in compressive strength of the gypsum products unless all the excess water is driven out. Theoretically there is about 8.8 percent of excess water in the hardened mass of the dental stone. The ultimate compressive strength of this stone is more than 55 MPa, when all of the excess water is lost. The compressive strength of wet specimens is half of this dry strength.

The tensile strength of dental plaster and stone is more important than compressive strength. If bending is likely to occur because of the application of a lateral force such as the removal of casts from a flexible impression, the teeth on the cast may be fractured.

The diametral tensile test is used to measured the tensile strength of the gypsum materials because of the brittle characteristic of the materials. The one hour tensile strength of dental plaster is reported to be around 2.3 MPa. The dry tensile strength of this plaster is about twice that of the wet strength, i.e approximately 4.1 MPa , after 40 hours at 45 ^{o}C. It has been noted by other investigators that the tensile strength of plaster either in a wet or dry condition is about one-half that of the high strength dental stone or one-fifth of the compressive strength of the plaster at the same condition.

2.5.1.2 Method of Assessing the Strength of Plaster of Paris

The method of accessing the strength of plaster of paris can be found in the specification for dental laboratory plaster (British Standard 4722:1971). In this specification, the procedure is to calculate the mean compressive strength of five specimens. ~~The~~ If the strength of each specimen ~~that~~ is 15 percent different from the mean strength is rejected and the mean strength of the remainder is recalculated. The whole process is repeated if three or more specimens are rejected.

2.5.2 Composite Resins

2.5.2.1 Introduction

The deficiencies of acrylic resins (Nelsen, Wolcott, Paffenbarger :1952, Paffenbarger, Nelsen, Sweeney:1953, Schouboe,Paffenbarger, Sweeney:1956, Caul, Sweeney, Paffenbarger :1956) and silicate cements (Paffenbarger, Schoonover, Souder:1938, Paffenbarger:1940, Paffenbarger :1943) lead to the investigation of composite resins system by Bowen (Bowen :1962). These resins system have given better mechanical strength, lower thermal coefficient of expansion, lower dimensional change on setting and higher resistance to abrasion (Dennison,Craig:1972, Macchi,Craig :1969).

A composite resin is most accurately defined as three-dimensional combination of at least two chemically different materials with a distinct interface separating the components (Phillips:1981,Craig:1981). They are the matrix phase, dispersed phase or reinforcing phase and surface inter-facial phase or coupling agent.

Bowen (Bowen:1979) has described the components involved in the development of the matrix phase for a typical composite resin. Some of the dental composite resin has also been described by Asmussen (Asmussen E:1975). The matrix phase usually consists of about 40 to 50 percent of the volume of the components. The main component of matrix phase is dimethacrylate monomer. The most commonly used dimethacrylate monomers are Bis-GMA, Urethane-diacrylates and a modified Bis-GMA without the hydroxy groups.

Viscosity controllers (methyl methacrylate (MMA), Ethyleneglycol dimethacrylate (EDMA) or triethyleneglycol dimethacrylate (TEDMA)) and inhibitors (4-methoxyphenol (PMP) and 2,4,6-tritertiarybutyl phenol (BHT)) are usually added to improve the handling properties and shelf-life (Lutz, Setcos , Phillips , Roulet:1983). The addition of thermochemical and photochemical initiators, accelerators and ultraviolet inhibitors provide appropriate polymerisation and colour stability (Craig R. G:1981, Bowen R.L:1979, Asmussen E:1975, Farah J.W, Dougherty E.W:1981, Vankerchhoven, Lambrechts, Van Beylen:1981).

Quartz, borosilicate glasses, ceramic glass and pyrolytic silica are commonly used reinforcing materials. Barium or other heavy metal glasses may also be used to provide radiopacity. These inorganic fillers give desirable physical properties such as rigidity, surface hardness, low shrinkage and low coefficient of thermal expansion.

The particles size of reinforcing fillers may vary from 10 nm for some of the pyrolytic silica to 100 μm for some quartz or glass fillers. The percentage of filler and the particles size varies among the products (Dennison, Craig:1972, Draughn, Harrison:1978, Jones, McCabe, Spence :1977, Raptis, Fan, Powers:1979).

The bond strength between the polymer matrix phase and inorganic reinforcing phase should be adequate enough to resist the transfer of stress. This requirement is accomplished by the use of a coupling agent that attaches to the inorganic filler phase and reacts with organic phase (matrix phase). Silanes are most commonly used as coupling agent (Sterman, Marsden:1963). The conversion of dimethacrylate monomers and monomers to a polymer matrix is initiated by free radicals created by chemical or photochemical dissociation of the initiator.

There are different methods of chemical activation, via the peroxide-amine initiation system. The most popular is the "two-paste" system. In this system two pastes each contain about 50 percent inorganic filler and 50 percent Bis-GMA by volume. One paste contain a benzoyl peroxide initiator and the other paste contain an activator (an organic amine).

Photochemical activation by visible light is commonly used. The initiator for the visible light activated composite resin is usually a diketone. In the presence of an amine, camphorquinone a commonly used diketone dissociates and free radicals are rapidly formed if correct wavelength and intensity of light are used. The blue light at 420 to 500 nm wavelength is used. The light is filtered to eliminate any stray ultra-violet radiation which might be present. The advantages of visible light-activated composite resins are:

(a) a faster and more complete cure with less porosity, allowing nearly instant finishing and providing superior physical properties.

(b) adequate working time for complicated restorations.

(c) optimization of the restoration quality of colour, translucent, opacity and morphology because of the use of an incremental technique to built up the restoration (Braden, Causton, Clarke:1976).

There are many methods available to characterize the composite resins (McCabe :1984). Characterization according to particle size and quantity of inorganic filler, and according to the method of activation are among two of the methods. There are three groups of composite resins which can be identified, by the particle size and quantity of inorganic filler. These groups are described below:

(i) Conventional composite resins

Generally these resins have a filler particle size range 1 to 100 μm. However they can be sub ~~divideed~~ divided into several groups of size 1 to 6 μm with mean of 4 μm, 15 to 20 μm with some larger particles of size 100 μm. Conventional composite resins usually have 75 to 80 percent of filler by weight.

(ii) Micro-filled composite resins

Pyrolytic silica particles in the range 10 to 100 nm with a mean of 40 nm are usually the content of these resins. The amount of filler content is normally within the range 30 to 60 weight percent.

(iii) Hybrid composite resins

Hybrid composite resins contain a blend of conventional and micro-filled composite materials. The proportion of each and total filler content may vary from one product to another. However most hybrid composite resins contain 78 to 85 percent of fillers by weight. Typical products would have 75 percent conventional particles and 7 percent pyrolytic silica.

There are two types of composite resins which can be identified when classification is made according to the activation system.

(i) Chemically activated composite resins

Chemical activated materials are supplied as two components, either a two paste system, a paste and liquid or a powder and liquid system. One component may contain a chemical initiator, the another contains a chemical activator.

(ii) Photochemical-activator composite resins

The materials are supplied as a single paste system, which contains a light-sensitive initiator, either ultra-violet or visible light activated. Ultra-violet light curing composite resins are not recommended on the basis of safety. The current composite resins are activated by light in the visible spectrum. The blue light activates an initiator system of camphoroquinone with a suitable amine.

Both chemically activated and light-activated composite resins are available in conventional, micro-filled or hybrid form.

2.5.2.2 Depth of Cure of Composite Resins

The presence of unreacted molecules in poorly polymerised composite resin has several detrimental effects. Regarding biocompatiblility, unreacted molecules may leach from the restoration and cause tissue irritation. It is also possible for secondary caries to develop. Mechanically, the restoration may be compromised by reducing the strength and hardness of the resins.

The depth of cure of composite resin has been found in "in-vitro" studies to depend on the composition of the composite resins, light source parameter, exposure time, storage time and condition, mould parameters, and the method of measurement (McCabe and Carrick:1986, Swartz, Phillips, Rhodes:1982, Kilian, Mullen:1980, Denyer, Shaw:1982, Pollack, Lewis:1981, Leung, Fan, Johnston:1982, Kilian:1979, Salako, Cook:1980, Tirtha, Fan, Dennison and Powers:1982, Murray, Yates, Newman:1981).

The maximum intensity of the light radiation beam is at the surface of the photoinitiated resin. As the light penetrates into the resins it will lose intensity as a result of the scattering and reflection of light by the fillers. For example the depth of cure of micro-filled composite resins is less than the depth of cure of conventional resins as the micro-filled has smaller and more numerous particles than conventional resin that has larger and fewer glass particles to scatter the light (Robert :1985).

The depth of cure has often been measured indirectly by measurement of the hardness of the material at specific depths (Cook:1980, Tirtha, Fan, Dennison and Powers:1982, Leung, Fan, and Johnston:1983, Leung, KAHN and Fan:1984, Steeters, Timmons, Mitchell:1983, Johnston, Leung, Fan:1985, Ferracace, Aday, Matsumoto, Marker:1986). There are several other methods that have been used to evaluate the depth of cure. The optical microscope was utilised by Murray (Murray, Yates, Newman:1981) and Newmen (Newman, Murray:1983) to determine the demarcation line between cured and uncured resin in the composite samples. The direct approach for evaluating the depth of cure is the infra-red spectroscopy (IR). The technique used in the method is to determine the percentage of the degree of conversion of carbon-carbon double-bonds converted into single bonds during polymerization reaction (Asmussen :1982, Ruyther, Oysead :1982, Ferrance:1985, Eliades, Vougiouklakis, Caputo:1988). Ferracane (Ferrance:1985), Asmussen (Asmussen:1982) and Eliades (Eliades, Vougiouklakis, Caputo:1988) have found that infra-red spectoroscopy correlates well with Knoop and Wallace hardness test. Tirtha et al (Tirtha, Fan, Dennison and Powers:1982) and Cook (Cook:1980) have compared Barcol and Knoop hardness test results, with the scraping method published by others and they have found the agreement among those.

It was suggested by Skeeters (Skeeters, Timmons, Mitchell :1983) and promoted by Johnston (Johnston, Leung, Fan:1985) that the depth of cure is defined as the level at which hardness value is equivalent to at least 90 percent of the hardness the top of the composite. Standard exposure time of 20 second is usually used for all visible light activated resins and the depth of cure of 2 to 2.5 mm of a light shade is normally obtained (Robert:1985). However an exposure time of 60 seconds is used by McCabe (McCabe and Carrick:1986). This gives 3 to 3.5 mm depth of cure.

2.5.2.3 Mechanical Properties of Composite Resins

The mechanical properties of composite resins depend upon the filler content, the type of filler, the efficiency of coupling between filler and resins, the degree of polymerization and the degree of porosity in the hardened material. The compressive strength of light-activated composite resin with 2 to 5 percent porosity is higher than the strength of chemically activated resin with 3 percent porosity (Robert:1985).

The compressive strength of the micro-filled composite are in the same range as the conventional composite resins. The majority of conventional composites have diametral tensile strengths about 40 MPa whereas the micro-filled composite have strengths of about 30 MPa. However the range of the value was from 26 to 56 MPa.

The hardness of set composite resin has been measured by Heath and Wilson (Heath and Wilson:1977). A value of hardness for the composite resin was approximately 55 KHN and was higher when compared to the unfilled acrylic resins of 15 KHN. The composite resins appear to withstand the abrasion of a tooth brush and a dentifrice somewhat better than the unfilled resins (Heath and Wilson:1977).

The mechanical properties of the materials are also affected by the amounts of porosity. Fracture of the materials is most likely to occur through the pores (Hannah and Combe

:1976). It has been estimated using ultrasonic testing, that the elastic constants of the products may be improved by a reduction in the amount of porosity (Nakayama, Hall, Grenoble et al:1974).

Porosity is present in all clinical composite resins and many researchers have reported this observation (Finger, Jorgensen :1977, Gjerdet , Hegdahl:1978, Fischel, Tay:1977, Gray, Gavin:1975,Hannah, Smith:1973, Hletanen, Rantanen:1976, Lee, Swartz, Smith:1969, Weitman, Eames:1975) and it varies from one product to another. The application of pressure to the mixed composite resin could reduce the percentage of porosity in the set resin (Gjerdet, Hegdahl :1978).

The properties of composite resins may vary from one product to another because the composition of the base resins are varied. The physical properties (Dennison et al:1972, Macchi et al:1969, Raptis et al:1979, Jones, McCabe, Spence:1977, Braden, Causton, Clarke:1976, Brady, Lee, Orlowski:1974, Finger, Jorgensen:1977, Gjerdet, Hegdahl T:1978, Harrington, McCabe:1976, Powers, Hostetler, Dennison:1979) and mechanical properties (Dennison and Craig:1972, Raptis, Fan, Powers:1979, Craig:1979, Draughn:1979, Hannah, Combe :1976, Lee, Orlowski:1977, Nakayama, Hall, Grenoble et al:1974, Powers , Allen, Craig:1974, Roberts, Powers, Craig 1977) for the conventional composite resins are widely discussed in literature.

* P.T.O.

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Occlusin, Opalux, Silux and P50 were the type of light activated composite resin used in this investigation. Occlusin and P50 are Hybrid composite resin while Silux is a Microfill composite resin and Opalux is macrofilled composite resin. Table 2.3 shows the mechanical strength of these materials.

Table 2.3 Some Mechanical strength of Composite Resin.

Composite Resin	Mean Compressive Strength	Mean Diametral Strength	Mean Flexural Strength
Occlusin	270(25)[5]	61(1.9)[10]	113(7)[5]
Opalux	-	-	130(10)[1] 124(15)[1] 131(12)[1]
Silux	-	36.2(3.6)[7] 36.2(3.6)[8]	44.7[6]
P50	-	71(5.6)[7] 71(5.6)[8]	-

Value in parentheses is a standard deviation.
Unit for mean strength is MPa.
- Strength value is not recorded in the literature..
[1]McCabe et al:1990 - 24 hours strength which were tested at different centre.
[5]Oysaed H and Ruyter I.E:1986 - 3 months strength.
[6]Bryant R.W and Mahler D.B:1986 - 7 days strength.
[7]Fraunhofer et al : 1989 - 24 hours strength.
[8]Fraunhofer J.A and Curtis P. Jr : 1989 - 24 hours strength.
[10] Chung K.H :1989 - 24 hours strength.

2.5.2.3.1 Method of Assessing the Strength of Composite Resins

The method of assessing the strength of composite resin can be found in the specification for resin-based dental filling materials (British Standard 5199:1975 and ISO 4049). In this specification, the procedure is to calculate the mean flexural strength of five specimens. The strength of each specimen that is 15 percent below the mean strength is rejected and the mean strength of the remainder is recalculated. The whole process is repeated if three or more specimens are rejected.

2.5.3 Dental Amalgam

2.5.3.1 Introduction

An amalgam by definition consists of two main parts, one of which is mercury (Black:1968, Robert:1985, Ralph:1982, Combe :1981, McCabe:1985) , the other is an alloy powder. Generally dental amalgam alloy powder consists of silver, tin, copper, and sometimes zinc. Mercury and amalgam alloy are mixed or triturated into a workable mass before being packed into the cavity. The reaction between mercury and alloy is termed as "amalgamation". It produces a hard silvery-gray restorative material.

Dental amalgam is the most widely used filling material for posterior teeth. It has been one of the most serviceable restorative materials being used in dentistry for over 100 years with a large measure of success.

An amalgam is reported to have been used first in 1826 in France , in the form of a silver-mercury paste (Robert :1985). In 1833 it was introduced into the United States. Some improvements were made by early investigators, particularly Elisha Townsend and J.F. Flagg. Townsend showed that an alloy composed of about equals parts of silver and tin was stronger than silver-copper coin alloy originally used for the silver paste. Flagg supported the finding and stated that the improvements made by Townsend could be achieved by changing the composition of silver up to 60 percent, 35 percent of tin and 5 percent copper. Addition of small quantities of gold and platinum, it has been shown do not produce added superior qualities in the hardened amalgam (Robert :1985).

Black's work has demonstrated that both the composition of amalgam alloy and the manipulation were important in the control of the strength of the final amalgam mass (Robert :1985). Black recommended that the amalgam alloy should contain approximately 68 percent silver with small quantities of tin, gold or copper and zinc (Robert :1985). With the exception of gold, these are the basic ingredients of present amalgam alloys.

Following Black's work, studies have been reported in England and the United States, respectively, by James McBain and A.W Gray on the setting reaction and methods of testing (Robert:1985). In 1929, the American Dental Association Specification adopted the composition suggested by Black (Black:1968) in ADA specification No 1 as a results of studies conducted by the National Bureau of Standards. In 1977 the composition limits of ADA Specification NO:1 were modified to permit compositions that included much more copper. This modification resulted from studies during the 1970's which showed that amalgam alloy with a higher copper contents may have superior properties.

Dental amalgam alloy has been broadly classified into two types according to the percentage of copper incorporated. The first type is known as conventional alloy, which contains less than 6 percent copper in the alloy (Combe:1981). The others contain as much as 30 percent Copper and the Copper enriched materials are called high copper alloys. The composition of the conventional alloys varies slightly from one product to another.

Some conventional amalgam products have excluded zinc from the alloy's ingredients. Zinc acts as "scavenger" during the production of the alloy. The oxidation of zinc occurs preferentially with the available oxygen than with other metals in the alloy. The "slag" of zinc oxide formed from the oxidation process can be easily removed. In the case of "zinc-free" alloy, the oxidation during melting is prevented by carrying out the alloying procedure in an inert atmosphere.

The shape and size of the alloy powder particles varies from one product to another. There are two methods commonly used to produce the alloy particles. Lathe cut alloy powder is produced from a prehomogenised ingot of alloy which is cut into shavings on a lathe. These particles are irregular in shape. They are graded according to size either fine or coarse. Spherical particle powder may be produced by atomisation (McCabe:1985) . Particles produced by this process are spherical or spheroidal in nature. The size of 10 to 37 μm has been suggested as typical of these products.

Some alloys contain a blend of lathe cut and spherical particles in order to increase the packing efficiency and to reduced the amount of mercury required to "wet" the particles and produce a workable mix.

Although these newer alloys have the same basic ingredient as conventional alloys, they contain much more copper, typically between 10 and 30 percent. Copper enriched alloys may be divided into the following types:

(i) Dispersion-modified alloys (or blended alloys). These alloys contain two parts by weight of conventional composition lathe cut particles and one part of spherical particles of a silver-copper "eutectic alloy"(ie approximately 70 percent silver plus 30 percent copper).

(ii) Single composition alloys. In these alloys all particles in the powder have approximately the same composition. There are different types of single composition alloy available,

(a) Ternary alloys in spherical form. These contain either 60 percent silver, 25 percent tin, 15 percent copper or 40 percent silver, 30 percent tin, 30 percent copper.

(b) Ternary alloys in spheroidal form. The composition is as (a).

(c) Quaternary alloys in spheroidal from. These contain 29 percent silver, 24 percent tin, 13 percent copper and 4 percent indium.

(iii) Blended alloys or dispersion modified alloys as (i) but the composition is different. It contains two parts by weight of ternary spherical alloys (60 percent silver, 25 percent tin and 15 percent copper) plus one part of conventional alloy. The latter alloy may be of spherical or fine grain lathe cut particles.

(iv) Admixture of conventional and copper alloys . These types of amalgam are supplied in the form of pellets in which are contained about 60 to 70 percent mercury.

2.5.3.2 Mechanical Properties of Dental Amalgam

A prime requisite for any restorative material is that of strength. Sufficient strength is required to resist fracture due to stresses developed in the oral environment. The strength of dental amalgam develops slowly to optimum strength. It may take up to 24 hours or more. The time required to reach optimum strength depends on the geometry of the alloy particle. The spherical particle alloys and fine grain lathe cut develop strength much faster than the conventional coarse lathe cut material and coarse-grain products (McCabe:1985).

The tensile strength and transverse strength are much lower than the compressive strength as amalgam is a brittle material. British Standard specification BS 2938:1985 for dental amalgam states that a minimum strength of 50 MPa must be achieved one hour after amalgamation is completed. The one hour compressive strength of both low and high copper content amalgam are in the range of 45 to 292 MPa (Malhofra, Asgar:1978). The tensile strength of both low and high copper amalgam have been reported to be in the range 48 to 70 MPa (Asgar, Arfaei, Mahler:1977). However the mechanical strength of amalgam is affected by many factors. The following factors may lead to the variation of the strength reported in the literature. It can be classified into two main factors:

(a) Specimen preparation variables

(i) Trituration process

Trituration is the process of mixing the amalgam alloys with the mercury. It is carried out by hand or using a mechanical mixer, called an amalgamator. Hand trituration is now out-dated. Capsulated materials are now extensively used. Trituration times of 5 to 20 seconds are normal with mechanical mixing compared with hand mixing of at least 40 seconds. Nagai et al (Nagai, Ohashi, Habu, Makino, Usui, Matuso, Hama, Kawamoto:1971) have pointed out that trituration time and the speed of the amalgamator effect the strength either in both traditional and high copper amalgam.

Variations in the trituration of silver amalgams as have been shown by many studies, influence their mechanical properties (Ralph:1982).

(ii) Mercury content

The amount of alloy and mercury to be used is measured by the weight ratio either of mercury to alloy or alloy-mercury. For example a alloy-mercury ratio of 5:6 indicates that 6 parts of mercury are used with 5 parts of alloy by weight. The alloy-mercury ratio may vary for different alloy composition, particles size and shapes, and heat treatment. The alloy-mercury ratio may vary between 5:8 and 10:8. The wetter mixes that contain more mercury usually obtained by hand mixing. The drier mixes are generally obtained by mechanical mixing and contain less mercury. Alloy-mercury ratio is the important factor in the control of the mechanical properties of the final set amalgam. Optimum properties of amalgam are believed to be achieved when the mercury content in the set amalgam is in the range between 44 and 48 percent (McCabe :1985). There appears to be no effect of the mercury content in the range 45 to 53 percent on the strength of the silver-tin amalgam (Swartz and Phillips:1956). However the strength decreases markedly with an increased in mercury percentage above 55 percent (Swartz and Phillips:1956).

(iii) Condensation

"Condensation" is the process in which the mixed amalgam material is packed into the cavity or mould for specimen preparation. The purpose of condensation is to pack the unattached gamma Ag-Sn phase particles as closely together as possible so that the greatest possible density is attained, with sufficient mercury present to insure complete continuity of the matrix phase between the remaining alloy particles, and to force the amalgam into all parts of the cavity preparation. This is done by incremental packing. The mercury rich material formed on the top surface of each increment is removed in order to minimise the final mercury content. There should be a minimal time delay between trituration and condensation as the properties of set amalgam are affected (Rupp, Paffenbarger, Patel:1980, Mahler:1970).

(iv) Porosity

Porosity and voids have been proven as possible factors affecting the mechanical properties of brittle materials. Voids were seen in micrographs of low copper, an admixed and single composition amalgam (Butts, Okare, Fairhurst:1981). In the studies of Wing (Wing:1965) the compressive strength of hardened amalgam has been affected by these factors. The porosity of amalgam is considered to be related to a number of factors. Plasticity is thought to be one of the factors (Mahler:1970).

(b) Test methods

(i) Strain rate

At low strain rates, some amalgams fractures with plastic deformation at failure. Vaidyanathan and his worker (Vaidyanathan ,Schulman:1979) have revealed that there is a strong dependence of dental amalgam failure mode with composition and low strain rates. The compressive strength of amalgam increases with increased rate of strain or rate of loading of the specimen (Vaidyanathan ,Schulman:1979, Sweeney, Burns 1961, Black:1968, Fairhurst:1966, Young, Wilsdore:1969, Taylor, Sweeney, Mahler, Dinger:1949).

Crosshead speeds of 0.05, 0.02, 0.005, 0.002 inch per minute were used in those investigations. The mode of failure of amalgam at the lower strain rate (i.e 0.002) was not catastrophic and a plastic deformation was observed. At strain rate of 0.005, some of the amalgam specimens have showed a catastrophic failure. Catastrophic failure is a characteristic of brittle materials. The strain rate corresponding to this behaviour should be taken to ensure the validity of the test for brittle materials.

(ii) Specimens geometry

The size and shape of the specimen, basically effects the mechanical strength of brittle materials. As already discussed, the basic requirement for compressive test specimen is that the ratio of length to diameter should be 2:1. Amalgam specimens of size 8 mm in length by 4 mm diameter are used by some of the investigators, and a size of 6 mm in length by 3 mm in diameter used by others. In fact even larger specimens are also being used. Eventhough the length/diameter ratio is similar, it has been reported by Taylor (Taylor:1983) that the compressive strength of these specimens is different. A smaller specimen length seem to have a larger compressive strength.

Early papers (Ward:1924, Taylor:1983, Sweeney:1940) have reported the tensile strength of dental amalgam. It has been concluded that the failures at the isthmus are due to the tensile strength (Mahler:1958). The tensile test was carried out using dumb-bell shaped specimens (Mario , Dickson:1962). Cylinder specimens of 8 mm in length by 4 mm diameter are also used as tensile test specimens. The tensile strength results from the specimens geometry is significantly different. It is important to mention that the test methods involved here were different. The specimens of dumb-bell shaped were pulled apart whereas the cylindrical specimens were compressed along their length. The other method used to measure tensile strength is transverse test (Mahler, Mitchem:1964). This method uses either bar or rod specimens. However variations of results have been reported. The other factor which comes into action when using the transverse test, is span/depth ratio.

(iii) Age of specimens

Some studies (Taylor, Sweeney, Mahler, Dinger:1949, Ralph:1949) have compared the compressive strength of amalgam with respect to time. The compressive strength was found to increase with an increase in time. One hour compressive strength was significantly lower than the 24 hours strength. The compressive strength has been observed to increase significantly after 7 days. The strength is then still increasing but very slowly after 7 days after amalgamation. Ralph (Ralph:1949) has recorded the compressive strength of six different amalgam, (small-, medium-, and coarse-grained alloy) which were available at that time, at aged six months.

* P.T.O

*

Amalcap and Dispersalloy were the dental amalgam used in this investigation. Amalcap is a conventional type and Dispersalloy is a zinc free dental amalgam. Table 2.4 shows the mechanical strength of these materials.

Table 2.4 Some Mechanical Strength Of Dental Amalgam.

Dental Amalgam	Mean Compressive Strength	Mean Diametral Strength	Mean Flexural Strength
Amalcap	331(40.2)[1] 414(11.1)[1] 390(16.7)[1]	33(4.46)[7]	-
Dispersalloy	-	-	103.5 [6]

Value in parentheses is a standard deviation.
Unit for mean strength is MPa.
- Strength value is not recorded in the literature..
[1]McCabe et al:1990- 24 hours strength which were tested at different centre.
[6]Bryant R.W and Mahler D.B:1986 - 7 days strength.
[7]Fraunhofer et al : 1989 - 24 hours strength.

2.5.3.2.1 Method of Assessing the Strength of Dental Amalgam

The method of assessing the strength of dental amalgam can be found in the specification for dental amalgam (British Standard 2938:1985). In this specification, the procedure is to calculate the mean compressive strength of five specimens. The strength of each specimen that is 15 percent below the mean strength is rejected and the mean strength of the remainder is recalculated. The whole process is repeated if three or more specimens are rejected.

POLYALKENOATE

2.5.4 GLASS ~~POLYALKENOATE~~ CEMENTS

2.5.4.1 Introduction

The invention of the Glass Polyalkenoate cements came from the development of the Silicate and Poly-Carboxylate System (Smith:1983). Dental Silicate cements have been available for many years. They were one of the first commercially available aesthetic restorative materials. They have a high compressive strength and their coefficient of thermal expansion matches that of the tooth tissues and they also have cariostatic properties due to the slow release of fluoride ions (Wilson:1975). However these materials are brittle, susceptible to chemical erosion, lack adhesion to tooth tissues and are highly irritant to pulp when freshly mixed as they have a low pH value i.e acidic (Phillips:1882)

Polycarboxylate cements are adhesive restorative materials which were developed to overcome the deficiencies of the Silicate cements. Polycarboxylate cements consist of Zinc Oxide powder and an aqueous solution of Polycarboxylate acid (Smith:1968). Interaction of the polyacid with Calcium ions in the tooth tissues will result in adhesion to the tooth (Smith:1968). However the structure of set cements is still susceptible to acidic attack (Crisp et al:1980).

Glass Polyalkenoate cements are derivatives of Silicate and Polycarboxylate cements. They consist of an ion-leachable glass powder and a Polyalkenoic acid (Wilson and Kent:1971,1972,1973). Glass Polyalkenoate cements may be supplied in the form of powder and liquid or a powder containing both the glass and freeze dried polymer (Polyalkenoic acid). The first type is known as "Conventional" Glass Polyalkenoate cements. They are prepared from an ion-leachable glass powder and a concentrated solution of a Polyalkenoic acid (Wilson and Kent:1973). The latter is known as the "Water-Hardening" type, where the ion leachable glass powder is blended with a dry polyacid powder and the cements are formed by mixing with water or dilute tartaric acid (McLean et al :1884)

2.5.4.2 Mechanical Properties

The mechanical properties of the Glass Polyalkenoate cements are inferior to Amalgam and Composite resins. There is no clear difference between the mechanical properties of "Conventional" and "Water-hardening" cements except the latter can be mixed with greater ease (Prosser et al:1984). The Glass Polyalkenoate cements are hard, brittle and capable of chemical adhesion to mineralised tooth tissue. Maximum hardness is reached 24 hours from mixing (Crisp et at:1976).

The compressive strength of the Glass Polyalkenoate cement is reported to be approximately 130 MPa which lies between the compressive strength of a Dental Silicate (200 MPa) and a Zinc Polycarboxylate cements (Current note 54: Australian Dental Journal 1976). The compressive strength the cements varies with time. (Crisp et al:1976).

* P.T.O.

2.5.4.2.1 Method of Assessing the Strength of Dental Cements

The method of assessing the strength of dental cements can be found in the specification for dental cements (British Standard 7214:1989). In this specification, the properties of dental cements are based on the Table of Performance Requirements. This Table is shown in the specification. The procedure is to calculate the compressive strength of five specimens. At least four of the five results should score above the minimum strength specified in the table inorder to pass the requirements. The material fails to meet the requirements if the strength of at least four of the five specimens score below the minimum strength specified in the table. In other cases, further 10 specimens should be prepared and the median of a total 15 specimens is recorded at the compressive strength.

CHAPTER THREE

SPECIMENS PREPARATION

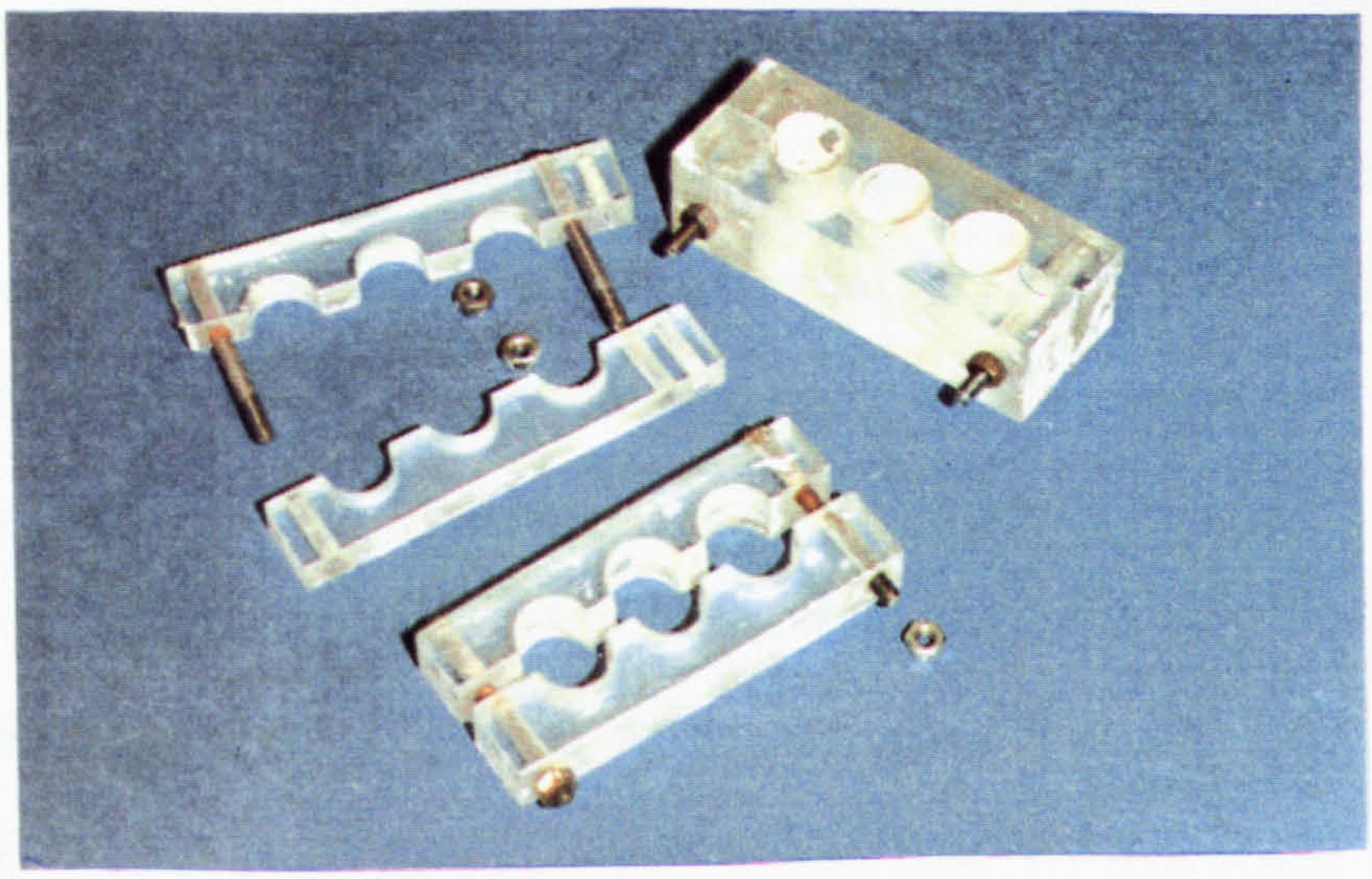
3.1 Introduction

The materials used in this investigation were plaster of paris, ~~porcelain~~, light-activated composite resins, dental amalgam and dental cement. Occlusin, Opalux, Silux and P50 were four types of light-activated composite resin used. Amalcap and Dispersalloy were two types of dental amalgam used. Ketac Fil and Ketac Silver were two types of dental cement used. Details of these materials are shown in the appendix C.

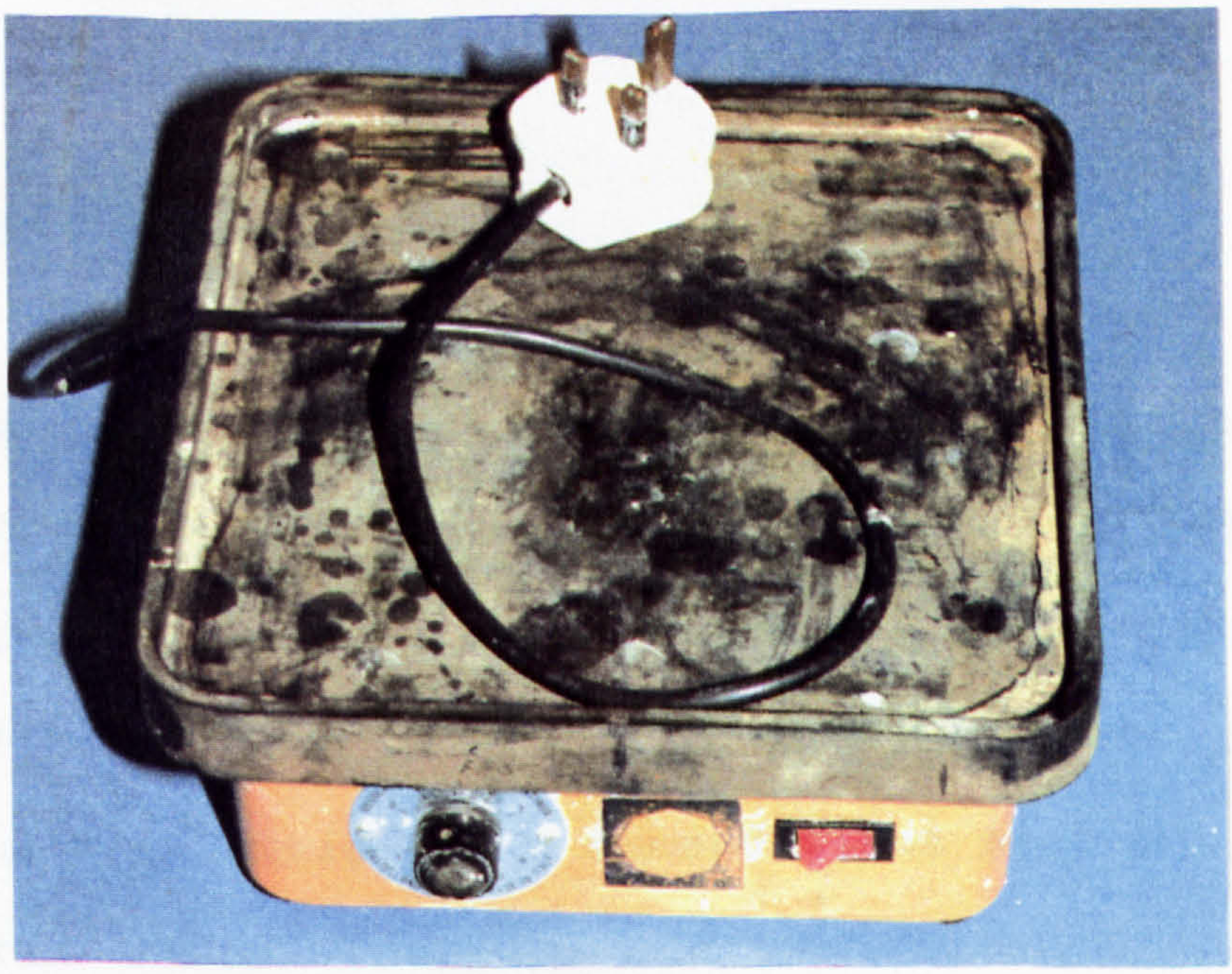
Specimens from each material were prepared according to the procedure as described below.

3.2 Plaster of Paris

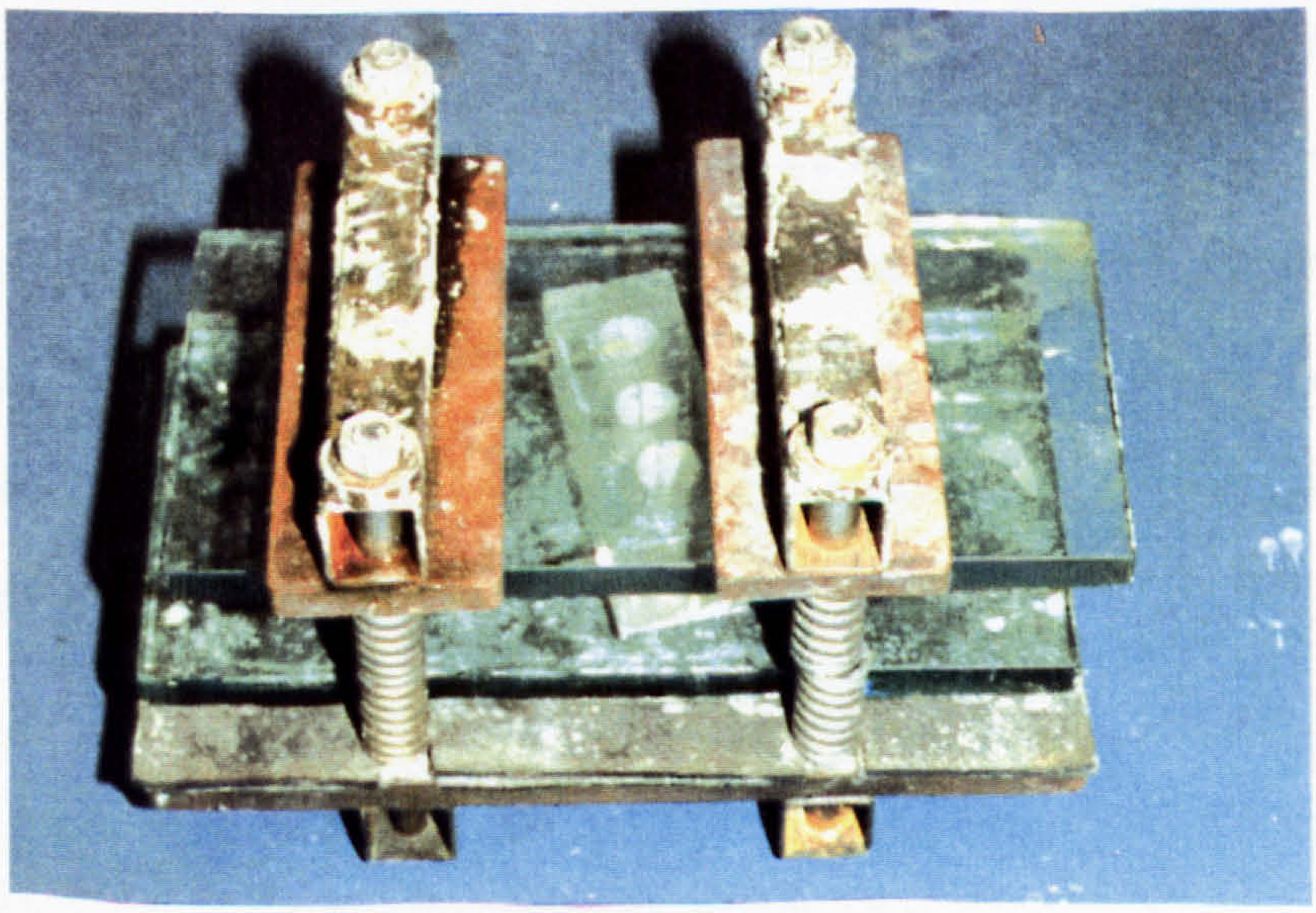
The plaster specimens were prepared in a split mould [Photograph A]. A series of moulds of constant diameter and varying length were made from Perspex. The powder and water were mixed inside a rubber type container with stainless steel spatula. Powder-water ratio of 2:1 was used (i.e 100 gram of powder was mixed with 50 ml of water) . The mould was placed over a glass slab and slightly overfilled with the mixture. The mould on the glass slab was vibrated for a few seconds with a vibrator (Photograph B), thus any



Photograph A
The Perspex Split Mould For Preparing The Plaster Specimens.



Photograph B
The Vibrator



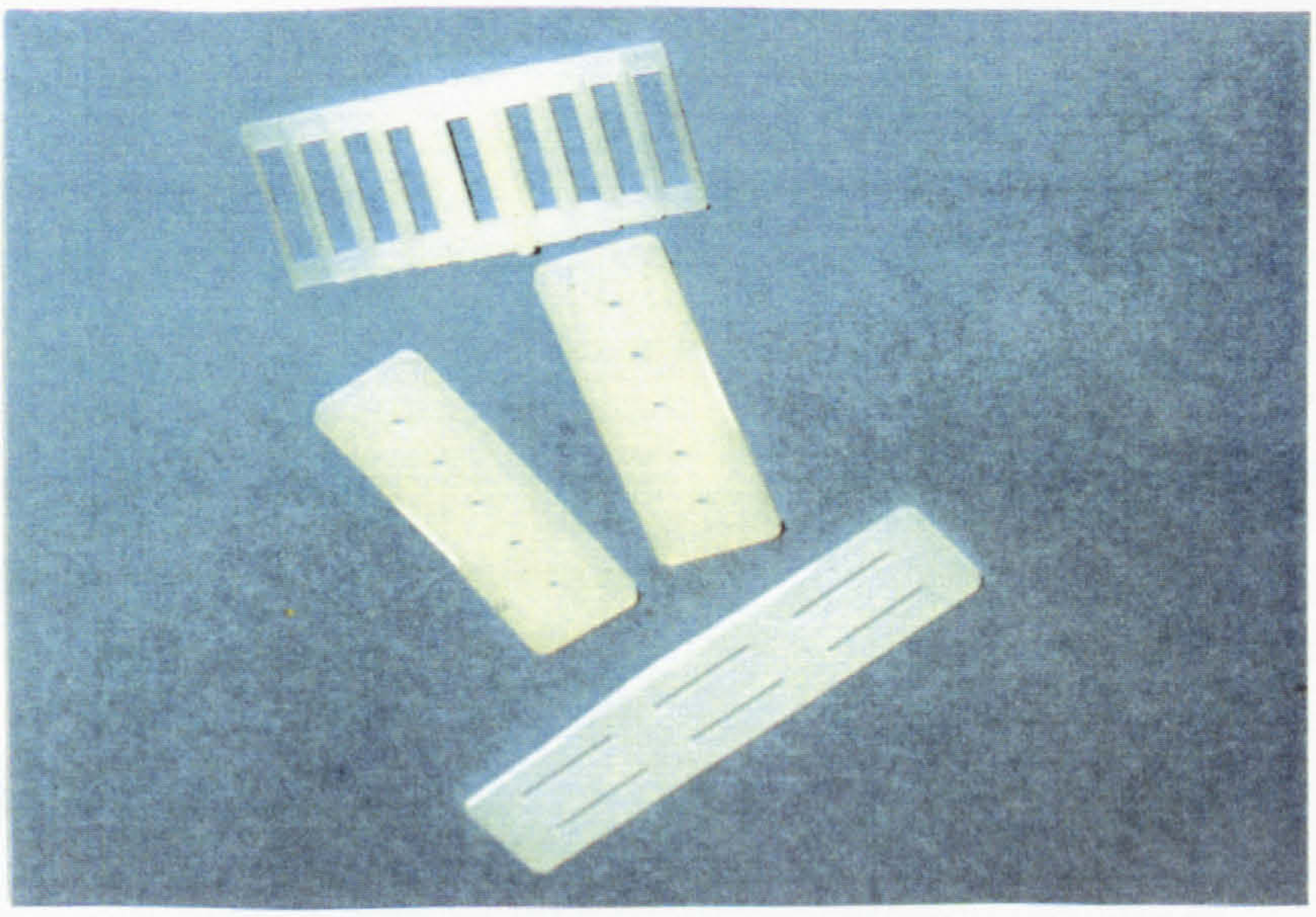
Photograph C
Plaster Mould in Clamping Position.

entrapped air in the mass could escape. Another glass slab was placed on the top of the mould and they were clamped until the glass plate contacted the ends of the mould. (Photograph C).

The material in the mould was allowed to set for 60 minutes in the clamped position before it was taken out. It was then left on a bench for seven days before testing. The specimens dimensions were measured prior to testing.

3.3 Composite Resin

The composite resin specimens were prepared in a polypropylene mould, as shown in Photograph D. The mould was placed over a plastic matrix strip on the glass slab and slightly overfilled with resin. The resin was covered with another matrix strip and a second glass slab was placed over the matrix strip. Pressure was then exerted on the top of the glass slab so as to extrude excess resin. The top glass slab was removed. Each uncured resin in the mould was light activated by using a Luxor unit (I.C.I England - Photograph E). After the top ends of the specimens have been cured, the mould was then turned over so that the other ends of the specimens could be cured. Thirty second period was used for the specimen thickness of 3 mm or less, 60 seconds for between 3 mm to 6 mm thick. Immediately after curing, the



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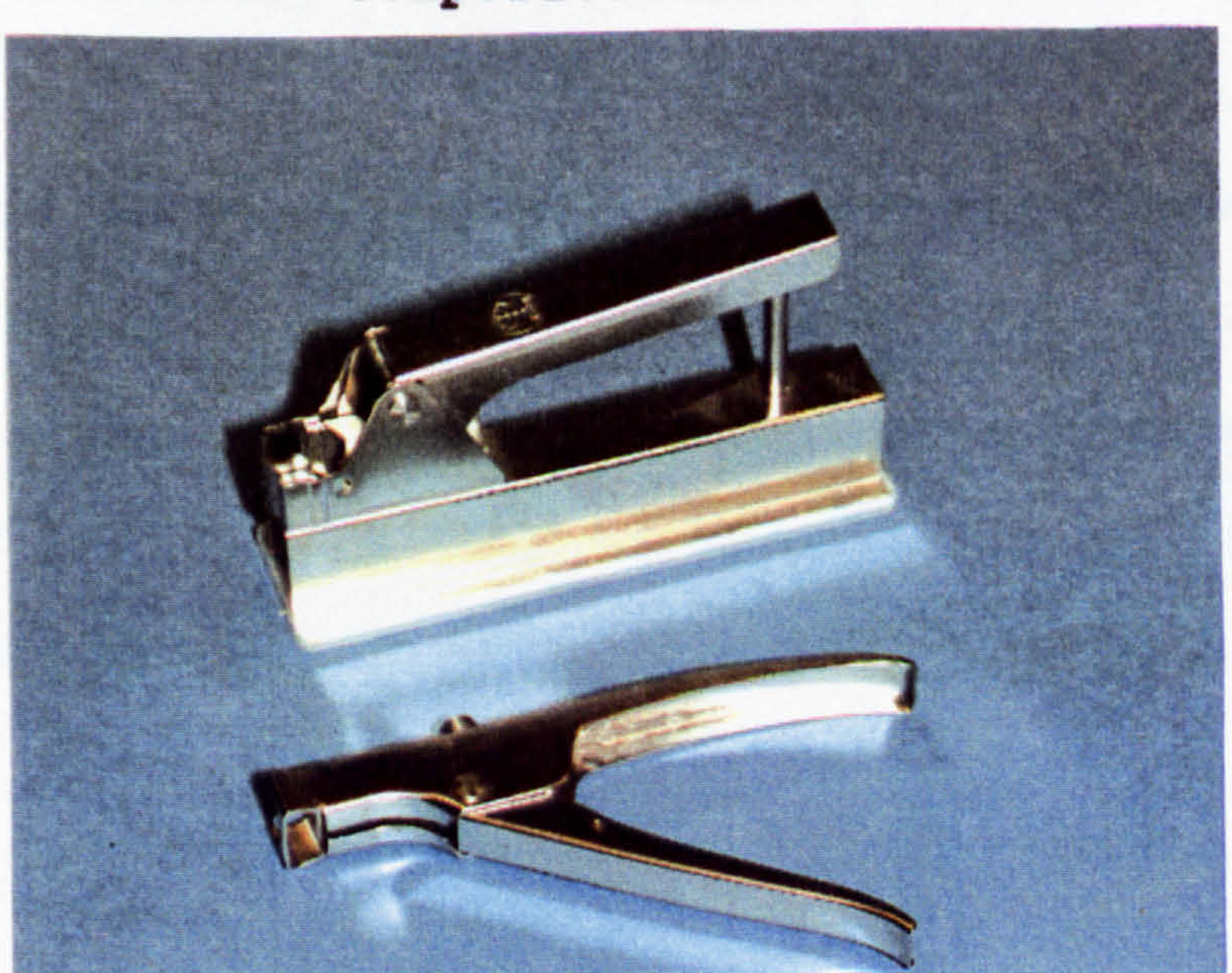
Photograph D
The Polypr~~y~~lene Mould For Preparing the Compressive,Diametral Tensile and Flexural Specimen.

Photograph E
The Light Activating Unit For Curing Light Activated Composite Resin.



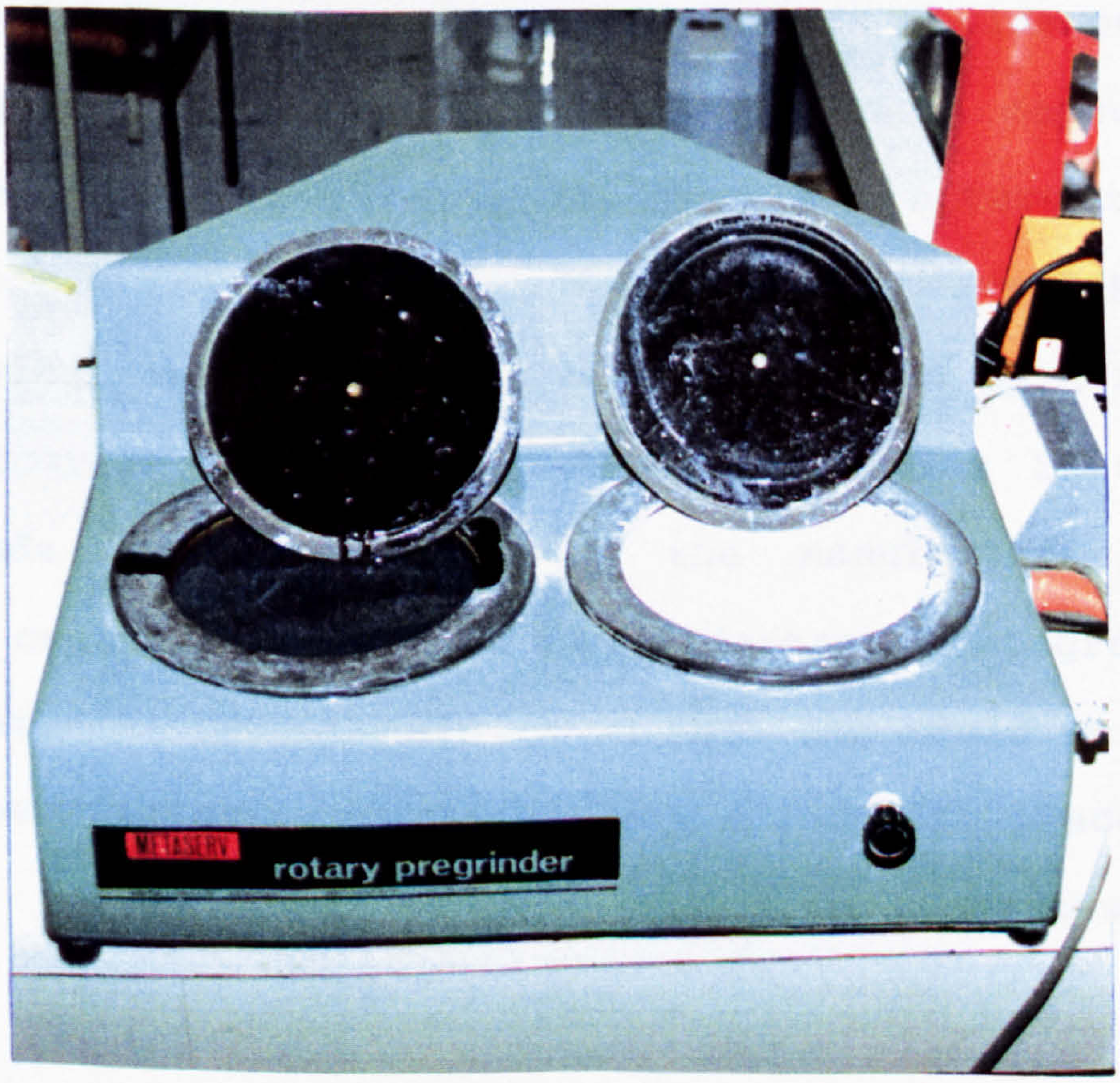
Photograph F
Capsule Injecter and Presser

matrix strips and specimens were removed from the mould and specimens dimension were taken. The specimens were then stored in distilled water at 37 ^{o}C prior to testing. Some of the specimens were bench dried.

3.4 Dental Amalgam

Dental amalgam specimens for the compressive test, diametral tensile test and flexural test were prepared in a poly-proplyene mould, as shown in Photograph D. Poly-proplyene sheet of specified thickness was cut into smaller pieces of size 20 mm width by 60 mm length. For the compressive test and diametral tensile test, five holes of specified diameter were drilled in each piece. While for the flexural test, ready made poly-proplyene moulds supplied by I.C.I (England) were used. A self-activated capsule containing amalgam alloys and mercury was activated by using Silamat activating unit (Photograph G) for 5 seconds(4-7 seconds as recommended by the manufacturer). The product was incrementally packed into the mould and slightly overfilled (The mould was previous placed on a glass slab). Pressure was exerted on the mould by using a piece of Perspex. The mould with the specimens in it was stored either in distilled water or bench dried for 7 days (depending on the type of test to be done) prior testing.

Photograph G
Silamat Activating Unit



Photograph H
The Rotary Pregrinder.

Prior to testing, the excess hardened material was removed by using an electrical grinding machine (Metaserv Rotary Pregrinder (Photograph H). A P800 waterproof silicon paper was used with the machine. After both surfaces of the mould were smoothed, the specimens were removed from the mould by carefully cutting the mould to the specimen edge using a Band-saw (Universal Cutting Machine Model BK1 (Photograph I).

3.5 Dental Cement

Dental cement specimens for the compressive test and diametral tensile test were prepared in a specially designed poly-proplyene mould, as shown in Photograph D). While for the flexural test, ready made poly-proplyene moulds supplied by I.C.I (England) were used. A dental cement capsule was pressed in a capsule presser in order to rupture the bag containing the poly-acid which would be then available for reaction with powder in the capsule when mixed by a Silamat unit (Photograph G). The capsule was mixed for 10 seconds (10 seconds as recommended by the manufacturer). The activated capsule was put in the injecter (Photograph F), and the material was then injected into the mould which was slightly overfilled. The mould was previously placed over a plastic matrix strip on a glass slab. Pressure was

Photograph I
Cutting Machine (Model BK1)

exerted on the top of the mould by using a piece of Perspex. The mould with the specimens in it was stored either in distilled water or bench dried for 7 days (depending on the type of test to be done) prior testing.

Prior to testing, the excess hardened material was removed by using an electrical grinding machine (Metaserv Rotary Pregrinder (Photograph H)). A P800 waterproof silicon paper was used with the machine. After both surfaces of the mould were smoothed, the specimens were taken from the mould by carefully cutting the mould to the specimen edge by using a Band-saw (Universal Cutting Machine Model BK1 (Photograph I).

CHAPTER FOUR

COMPRESSIVE TEST

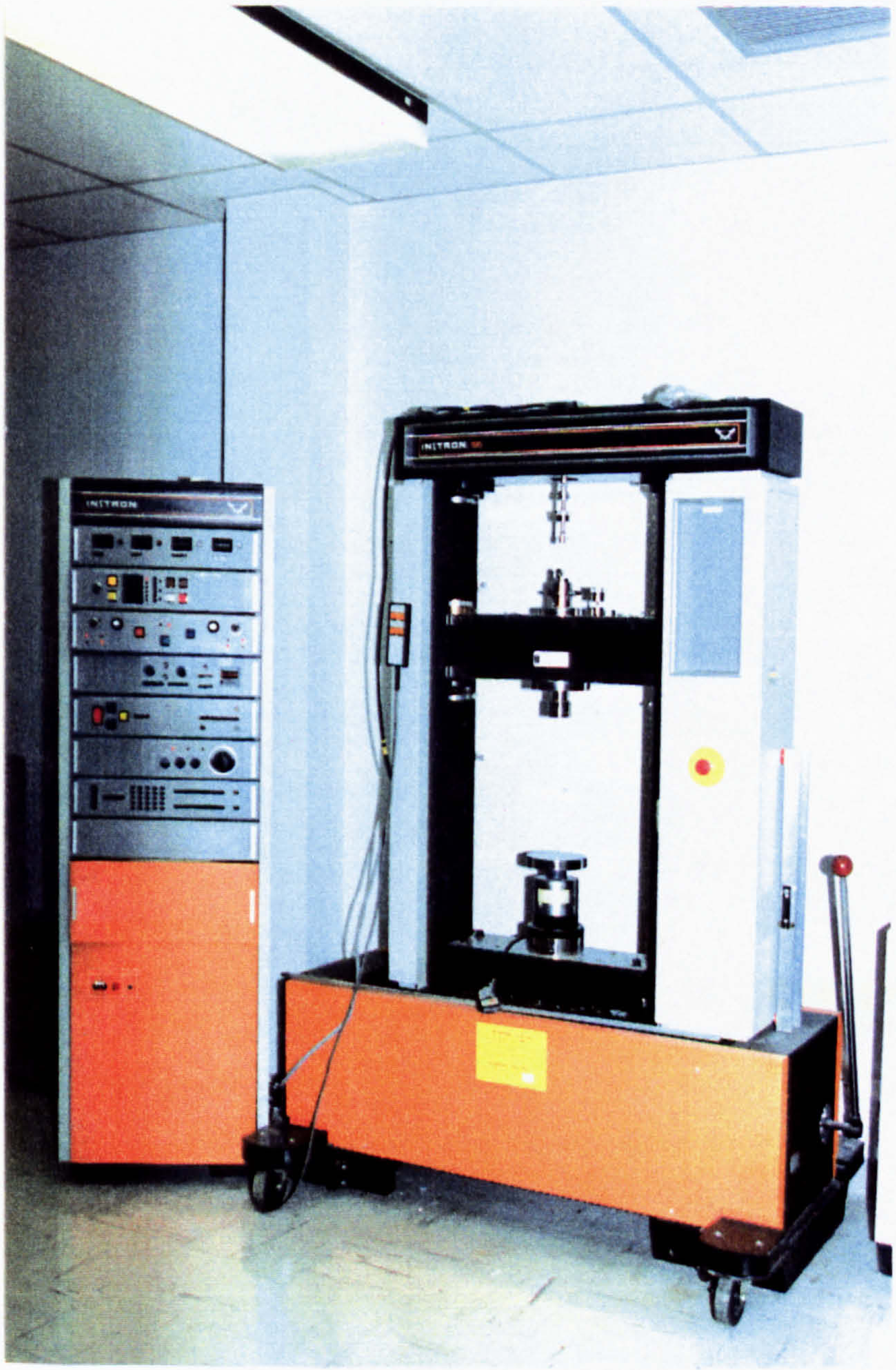
4.1 The Effect Of The Specimen Size And Crosshead Speed On The Compressive Strength.

This part of the investigation was conducted to evaluate the effect of test parameters on the compressive strength of some brittle dental restorative materials. The parameters were:-

(a) the effect of crosshead speed on the compressive strength.

(b) the effect of specimen size on the compressive strength.

These investigations were conducted firstly, to study the effect of crosshead speed on the compressive strength of the brittle dental materials. The crosshead speed that is most relevant for the compressive test would be determined. It would be used in further investigations to determine the strength parameters of dental restorative materials. Secondly, the effect of specimen size on the compressive test of brittle dental materials was investigated. The most relevent specimen size would be determined and would be used in further investigations to determine the strength parameters of the dental restorative materials.



Photograph J

An Instron Universal Testing Machine (Model 1195)

The materials used in this investigation were Plaster of Paris and light-cured composite resins (Occlusin and Opalux). Crosshead speeds of 0.1, 0.5, 1.0 and 10 mm per minute were used for all the tests.

4.2 Methods

4.2.1 Plaster of Paris

For the compressive test of Plaster of Paris, specimens of four different diameter-length ratios were prepared. The various sizes of the specimens were obtained from a mould of constant 18 mm diameter. The depth of the specimens were 15 mm , 20 mm , 25 mm and 30 mm. Four crosshead speeds were selected. They were, ranging from the slowest speed of 0.1 mm per minute to a fastest speed of 10 mm per minute. The two intermediate rates were 0.5 mm per minute and 1 mm per minute. For each size of specimen, a total of 120 specimens were prepared i.e 30 specimen for every Crosshead ~~cross head~~ speed. Hence a grand total of 480 specimens were tested.

The specimens were prepared in accordance to the procedure described in chapter three. All the tests were carried out using the Instron Universal testing machine (Model 1195) that is shown in Photograph J. The data was analysed by the computer program called `strength analysis'. This program was written in `fortran computer language' which is shown in appendix A. This program calculates the Weibull parameters such as Weibull modulus, characteristic strength, correlation coefficient, standard error of modulus and calculates the stress at 0.01, 1.0 and 99.99 percent probability of failure. The program also calculates the mean strength, deviation coefficient and stress at 0.01, 1.0 and 99.99 percent probability of failure for the Normal and Student-t distributions. A sample output of the program is shown in appendix B. A sample calculations for the stress at 0.01, 1 and 99.99 percent failure probability for the Normal statistic is also shown in appendix B.

4.2.2 Opalux

For the compressive strength test of Opalux, specimens with a diameter/length ratio of 1:2 were prepared. They were 2.5 mm diameter by 5 mm in length and 3 mm diameter by 6 mm in length. The crosshead speeds of 0.1 mm per minute, 0.5 mm per minute, 1 mm per minute and 10 mm per minute were used. Thirty specimens were prepared for each crosshead speed and size. Hence a total of 240 specimens were tested. They were stored in distilled water at 37 ^{o}C for seven days prior to testing. The aim of this experiment was to investigate the effect of crosshead speed on the compressive strength of Opalux at different specimen sizes. The diameter/length ratio of 1:2 was used because the length of the cylindrical specimen for the compressive test should be twice the diameter as this has been mentioned in chapter two (section 2.2.2.2).

Another group of compressive specimens of 2 mm, 3 mm, 4 mm, 5 mm and 6 mm diameter by 4 mm length, 2.5 mm, 3 mm, 4 mm and 6 mm diameter by 5 mm length, and 3 mm, 4 mm and 5 mm diameter by 6 mm length were prepared. They were stored in distilled water at 37 °C for seven days prior to testing. The ~~cross-head~~ crosshead speed of 0.1 mm per minute was used. Thirty specimens were tested at each specimen size. Hence a total of 360 specimens were tested. The aim of this experiment was to investigate the effect of specimen size on the compressive strength of Opalux at a low crosshead speed (0.1 mm per minute).

The specimens were prepared in accordance to the procedure described in chapter three. All the tests were carried out using the Instron Universal testing machine (Model 1195) that is shown in Photograph J. The data was analysed by the computer program described in section 4.2.1.

4.2.3 Occlusin

For the compressive strength test of Occlusin, a group of specimens of 4 mm diameter by 6 mm length, 5 mm diameter by 6 mm length and 6 mm in diameter by 6 mm in length were prepared. They were stored in distilled water at 37 °C for seven days prior to testing. Four crosshead ~~cross head~~ speeds were evaluated with each specimen size, they were 0.1 mm per minute, 0.5 mm per minute, 1 mm per minute and 10 mm per minute. Thirty specimens were tested at each crosshead speed. Hence a total of 360 specimens were tested. The aim of this experiment was to investigate the effect of specimen size and crosshead speed on the compressive strength of Occlusin. In this experiment different diameter/length ratios were tested.

Another group of specimens of 3 mm diameter by 3 mm length, 3 mm diameter by 6 mm length, 4 mm diameter by 6 mm length, 5 mm diameter by 6 mm length and 6 mm in diameter by 6 mm in length wsa prepared. These specimens were bench dried for seven days prior to testing. Four crosshead ~~cross head~~ speeds were evaluated with each specimen size. They were 0.1 mm per minute, 0.5 mm per minute, 1 mm per minute and 10 mm per minute. Thirty specimens were tested at each crosshead speed. Hence a total of 480 specimens were tested. The aim of this experiment was the same as in the above paragraph i.e to investigate the effect of specimen size and crosshead speed on the compressive strength of Occlusin. But in this experiment, the specimens were bench dried. Therefore the effect of storage condition on compressive strength of Occlusin could be studied.

The specimens were prepared in accordance to the procedure described in chapter three. All the tests were carried out by using the Instron Universal testing machine (Model 1195) that is shown in Photograph J. The data was analysed by the computer program described in section 4.2.1 .

4.3 Results and Discussion

Data from the mechanical test for each type of material was analysed by the "Strength analysis". As previously mentioned this was carried out by the computer. The output of the program such as Weibull modulus, standard error of modulus, characteristic strength and stress at various levels of failure probability were recorded. A typical set of data and a print out of the Weibull analysis is shown in the appendix B.

Mean strength, percentage of deviation coefficient and stress at various levels of failure probability from the Normal distribution were also calculated. Stresses at various levels of probability from the Weibull distribution, the Normal and "t" distributions were compared.

The results of all the mechanical tests for all types of material under investigation are put in the form of Tables for the analysis of the Weibull distribution, Normal and "t" distributions. A graphical representation of the results by the Weibull distribution is shown in the Figures.

TABLE 4.3.1.1

Summary of Weibull analysis-Compressive strength of various sizes* of Plaster specimens which are tested at crosshead speed of 10mm/min.

Specimen Size	1	2	3	4
Weibull Modulus	8.4	6.4	6.0	9.5
Characteristic Strength+	22.7	21.0	22.5	19.3
Standard Error of Modulus	0.23	0.32	0.10	0.39
Coeff. of Correlation	0.98	0.94	0.99	0.95
Mean Strength+	21.5	19.6	20.9	18.3
Deviation Coefficient (%)	12.8	16.3	17.7	10.8
Stress+ at Failure Probability				
0.01% - Weibull	7.6	5.0	4.8	7.3
Normal	19.6	17.4	18.8	20.7
1% - Weibull	13.1	10.2	10.4	11.9
Normal	20.3	18.2	19.3	21.1
99.99% - Weibull	27.2	26.8	29.0	22.6
Normal	23.4	21.8	23.4	24.7

* Size 1 = 18mm diameter by 15mm length, size 2 = 18mm diameter by 20mm length, size 3 = 18mm diameter by 25mm length and size 4 = 18mm diameter by 30mm length.
\+ unit in Mpa.
One-way analysis of variance - A significant difference between compressive strength and Specimen size ($P<0.05$).

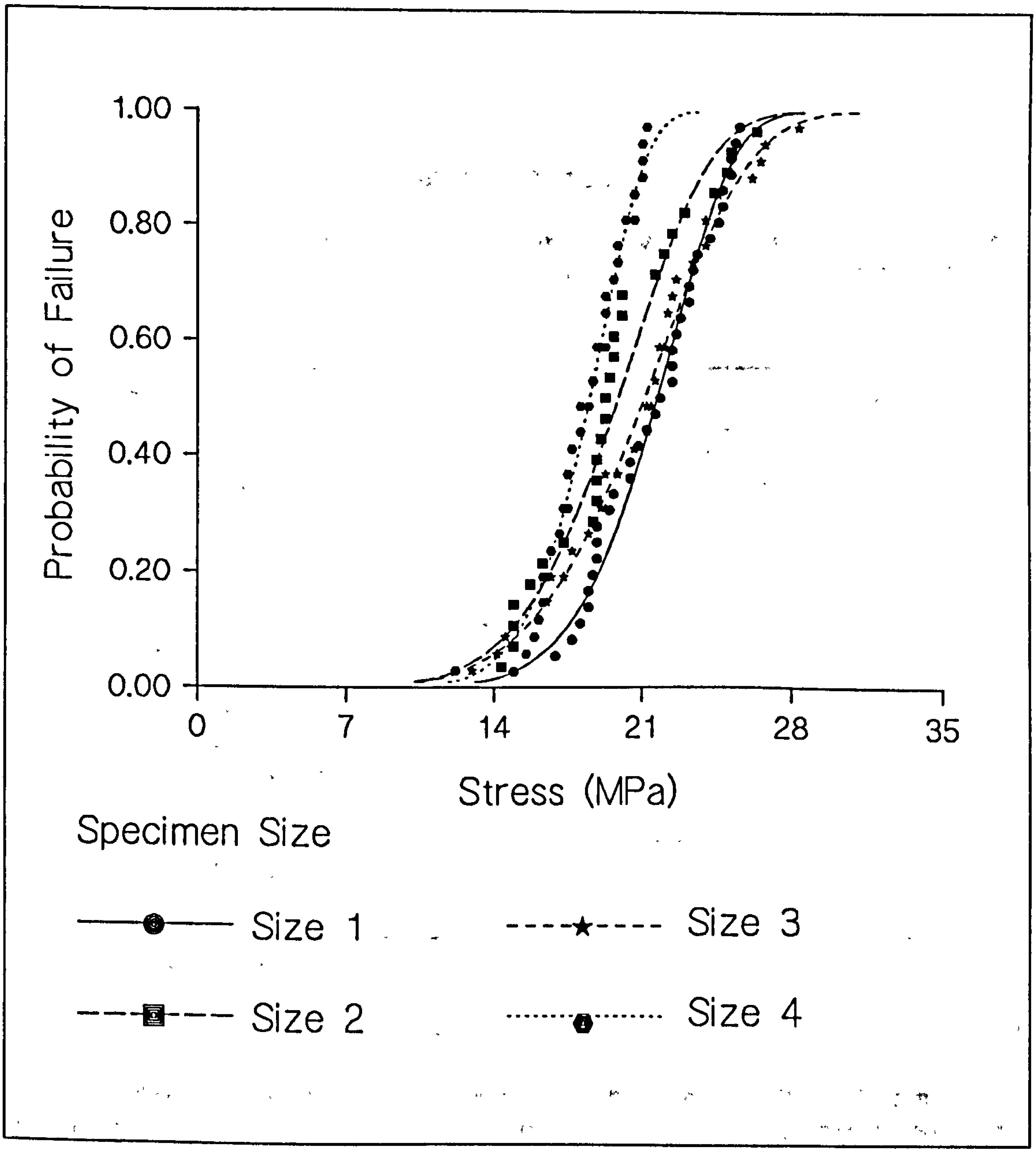


FIGURE 4.3.1.1

Compressive Strength of Plaster-Probability of failure versus compressive stress of the specimen of various size at crosshead speed 10mm/min.

Size 1 = 18mm diameter by 15mm length, size 2 = 18mm diameter by 20mm length, size 3 = 18mm diameter by 25mm length and size 4 = 18mm diameter by 30mm length.

TABLE 4.3.1.2

Summary of Weibull analysis-Compressive strength of various sizes* of Plaster specimens which are tested at crosshead speed of 1mm/min.

Specimen Size	1	2	3	4
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	8.5 24.0 0.27 0.97	8.8 23.7 0.16 0.99	6.2 20.2 0.19 0.99	6.7 21.0 0.23 0.96
Mean Strength+ Deviation Coefficient (%)	22.7 12.8	22.4 12.2	18.8 12.2	19.6 16.2
Stress+ at Failure Probability				
0.01% - Weibull Normal	8.1 20.7	8.5 22.4	4.5 16.9	5.3 16.9
1% - Weibull Normal	10.6 21.5	14.0 23.1	9.6 17.5	10.5 17.5
99.99% - Weibull Normal	28.8 24.7	28.2 26.4	25.8 19.9	26.4 19.9

* Size 1 = 18mm diameter by 15mm length, size 2 = 18mm diameter by 20mm length, size 3 = 18mm diameter by 25mm length and size 4 = 18mm diameter by 30mm length.
\+ unit in Mpa.
One-way analysis of variance - A significant difference between compressive strength and Specimen size (P<0.001).

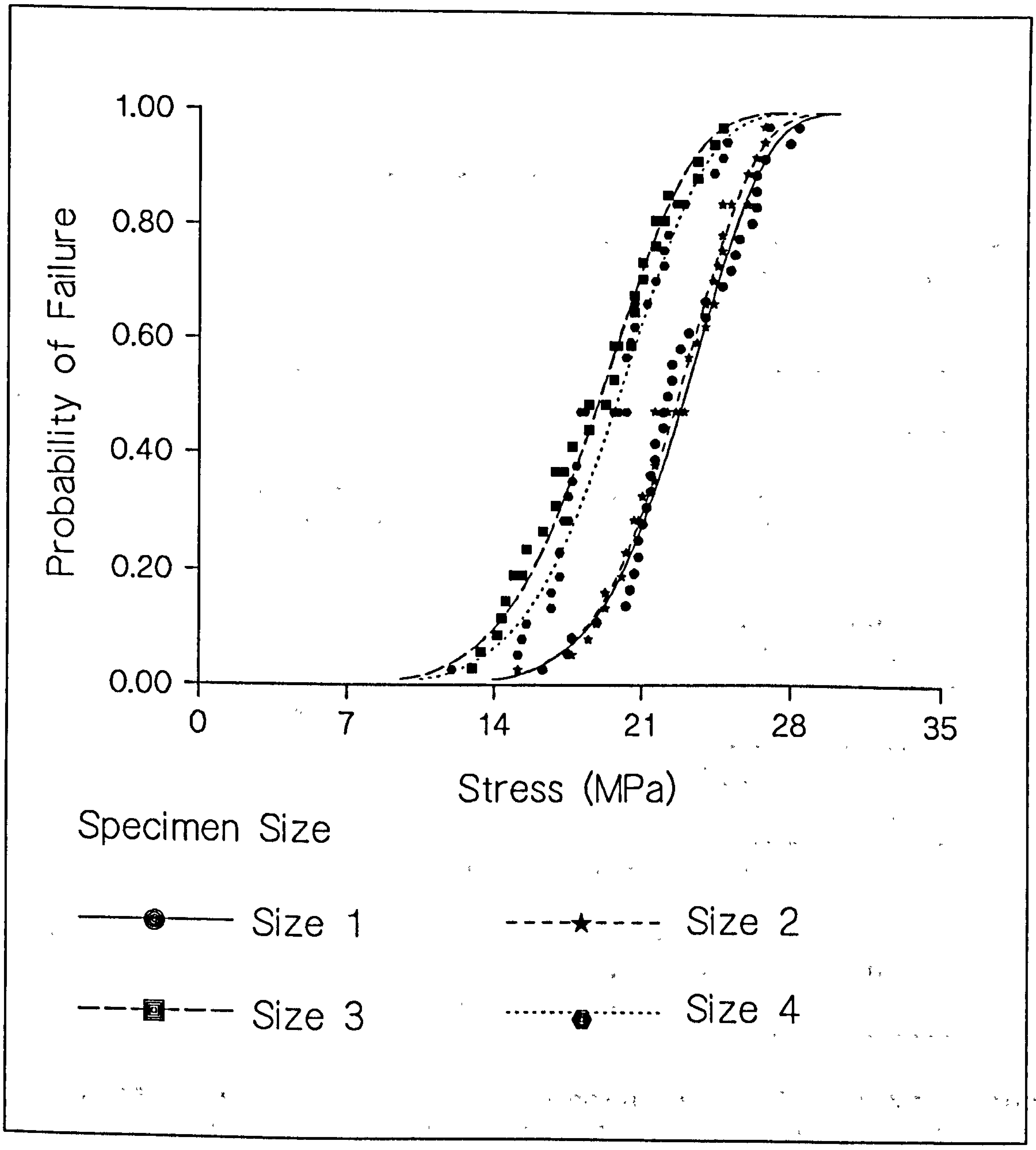


FIGURE 4.3.1.2

Compressive strength of Plaster-Probability of failure versus compressive stress of the Specimen of VariousSizes at crosshead speed 1mm/min.

Size 1 = 18mm diameter by 15mm length, size 2 = 18mm diameter by 20mm length, size 3 = 18mm diameter by 25mm length and size 4 = 18mm diameter by 30mm length.

TABLE 4.3.1.3

Summary of Weibull analysis-Compressive strength of various sizes* of Plaster specimens which are tested at crosshead speed of 0.5mm/min.

Specimen Size	1	2	3	4
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	8.7 24.2 0.23 0.98	10.1 23.1 0.31 0.97	6.5 22.2 0.40 0.88	8.07 21.6 0.42 0.92
Mean Strength+ Deviation Coefficient (%)	23.0 12.4	22.0 10.8	20.7 16.8	20.3 13.0
Stress+ at Failure Probability				
0.01% - Weibull Normal	8.4 21.1	9.3 20.4	5.4 18.4	6.8 18.4
1% - Weibull Normal	14.3 21.8	14.6 21.0	7.7 19.2	12.1 19.2
99.99% - Weibull Normal	28.9 24.9	26.9 23.6	28.1 23.1	26.1 23.1

* Size 1 = 18mm diameter by 15mm length, size 2 = 18mm diameter by 20mm length, size 3 = 18mm diameter by 25mm length and size 4 = 18mm diameter by 30mm length.
+ unit in Mpa.
One-way analysis of variance- highly Significant difference between compressive strength and Specimen size (P<0.01).

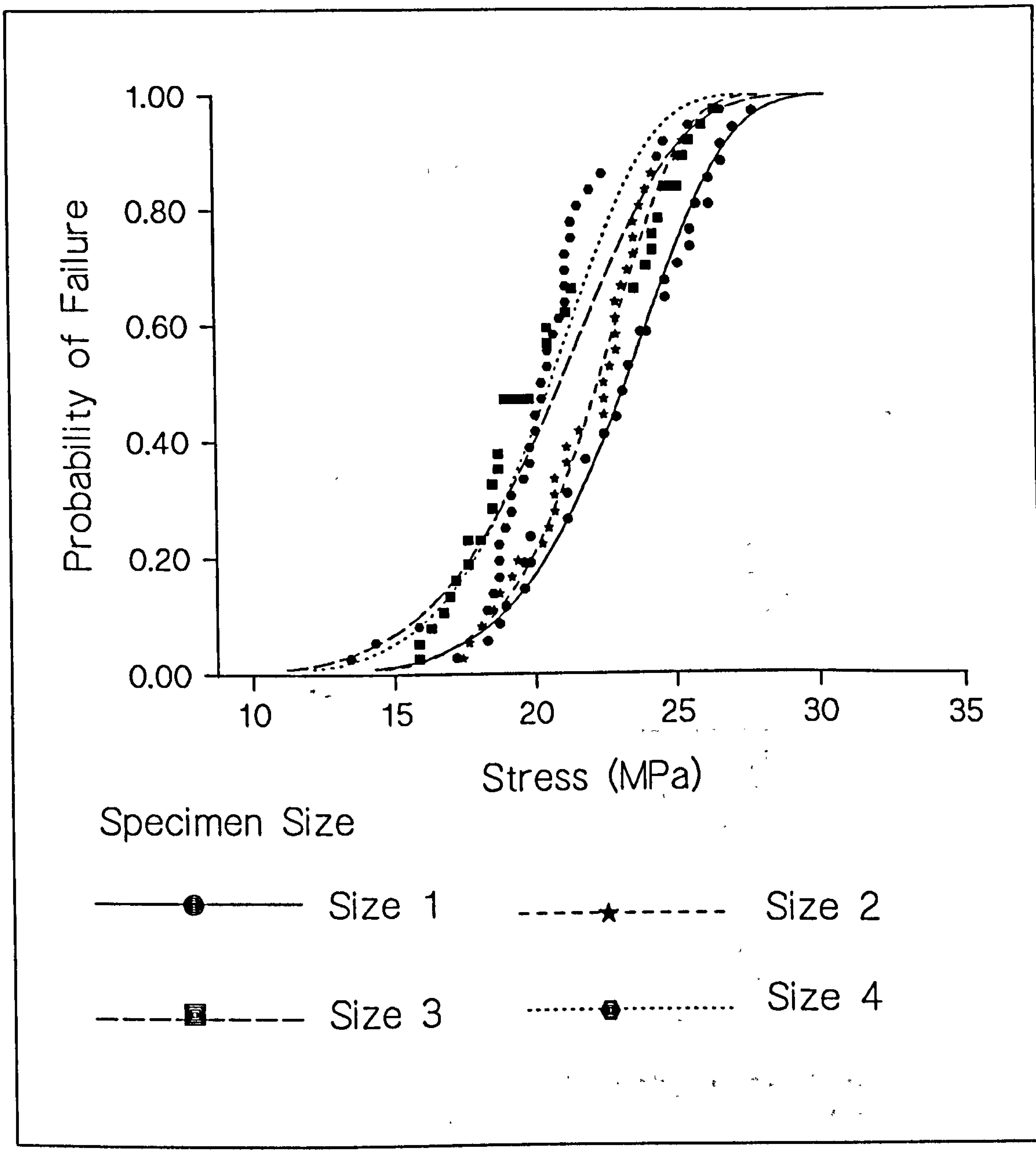


FIGURE 4.3.1.3

Compressive strength of Plaster-Probability of failure versus compressive stress of the specimen of various sizes at crosshead speed 0.5mm/min.

Size 1 = 18mm diameter by 15mm length, size 2 = 18mm diameter by 20mm length, size 3 = 18mm diameter by 25mm length and size 4 = 18mm diameter by 30mm length.

TABLE 4.3.1.4

Summary of Weibull analysis-Compressive strength of various sizes* of Plaster specimens which are tested at crosshead speed of 0.1mm/min.

Specimen Size		1	2	3	4
Weibull Modulus		8.00	7.9	9.0	9.1
Characteristic Strength+		23.2	22.9	23.1	21.9
Standard Error of Modulus		0.16	0.29	0.54	0.26
Coeff. of Correlation		0.99	0.96	0.98	0.97
Mean Strength+		21.9	21.6	21.9	20.8
Deviation Coefficient (%)		13.2	13.9	11.9	12.2
Stress+ at Failure Probability					
0.01%	- Weibull	7.3	7.2	8.5	7.9
	- Normal	19.9	19.6	20.1	20.1
1%	- Weibull	13.0	12.8	14.0	13.2
	- Normal	20.7	20.3	20.8	20.8
99.99%	- Weibull	28.1	27.3	27.3	26.0
	- Normal	23.8	23.6	23.7	23.7

* Size 1 = 18mm diameter by 15mm length, size 2 = 18mm diameter by 20mm length, size 3 = 18mm diameter by 25mm length and size 4 = 18mm diameter by 30mm length.
+ unit in Mpa.
One-way analysis of variance- highly no Significant difference between compressive strength and Specimen size (P>0.5).

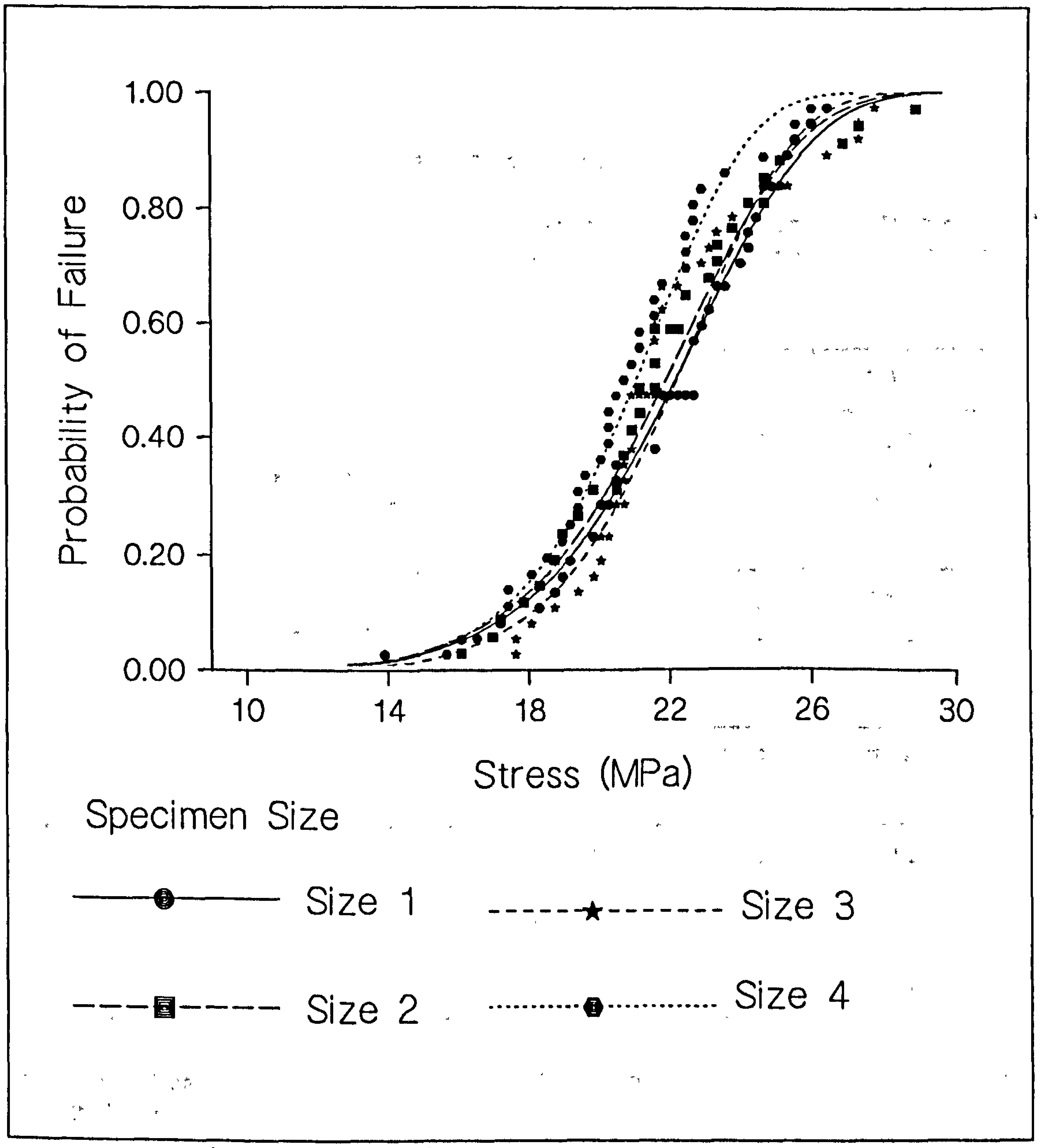


FIGURE 4.3.1.4

Compressive strength of Plaster-Probability of failure versus compressive stress of the specimen of various sizes at crosshead speed 0.1mm/min.

Size 1 = 18mm diameter by 15mm length, size 2 = 18mm diameter by 20mm length, size 3 = 18mm diameter by 25mm length and size 4 = 18mm diameter by 30mm length.

TABLE 4.3.1.5

Summary of Weibull Analysis-Compressive strength of Plaster that carried out for specimen size 1* which is tested at various crosshead speeds.

Crosshead Speed (mm/min)	0.1	0.5	1.0	10.0
Weibull Modulus	8.7	8.5	8.0	8.4
Characteristic Strength+	24.2	24.0	23.2	22.7
Standard Error of Modulus	0.23	0.27	0.16	0.23
Coeff. of Correlation	0.98	0.97	0.99	0.98
Mean Strength+	23.0	22.7	21.9	21.5
Deviation Coefficient (%)	12.4	12.8	13.2	12.8
Stress+ at Failure Probability				
0.01% - Weibull	8.4	8.1	7.3	7.6
Normal	21.1	19.9	19.9	19.6
1% - Weibull	14.3	14.0	13.0	13.1
Normal	21.8	21.5	20.7	20.3
99.99% - Weibull	28.9	28.8	28.1	27.2
Normal	24.9	24.7	23.8	23.4

* Size 1 = 18mm diameter by 15mm length.
+ unit in Mpa.
One-way analysis of variance- no Significant difference between compressive strength and crosshead speed (P>0.05).

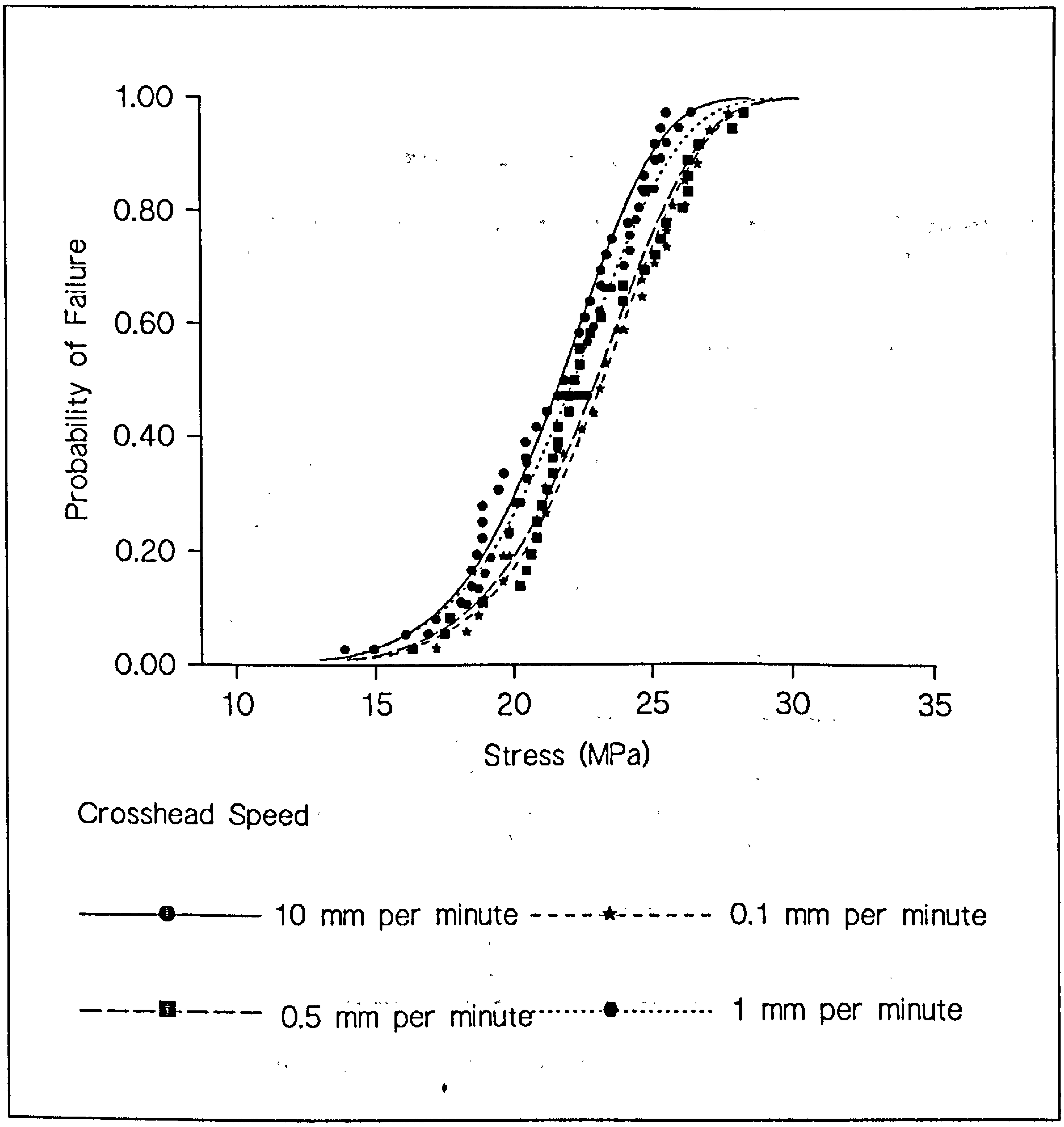


FIGURE 4.3.1.5

Compressive strength of Plaster-Probability of failure versus compressive stress for the specimen size 1 which is tested at various crosshead speeds.

Size 1 = 18mm diameter by 15mm length

TABLE 4.3.1.6

Summary of Weibull Analysis-Compressive strength of Plaster that carried out for specimen size 2 which is tested at various crosshead speeds.

Crosshead Speed (mm/min)	0.1	0.5	1.0	10.0
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	7.9 22.9 0.29 0.96	5.4 22.2 0.40 0.88	6.2 20.2 19 0.97	6.4 21.0 0.32 0.94
Mean Strength+ Deviation Coefficient (%)	21.6 13.9	20.7 16.8	18.8 17.4	19.6 16.3
Stress+ at Failure Probability				
0.01% - Weibull Normal	7.2 19.6	5.4 18.4	4.5 16.6	5.0 17.4
1% - Weibull Normal	12.8 20.3	11.0 19.2	9.6 17.4	10.2 18.2
99.99% - Weibull Normal	27.8 23.6	28.1 23.0	25.8 21.0	26.8 21.8

* Size 2 = 18mm diameter by 20mm length
\+ unit in Mpa.
One-way analysis of variance- very highly significant difference between compressive strength and crosshead speed ($P<0.001$).

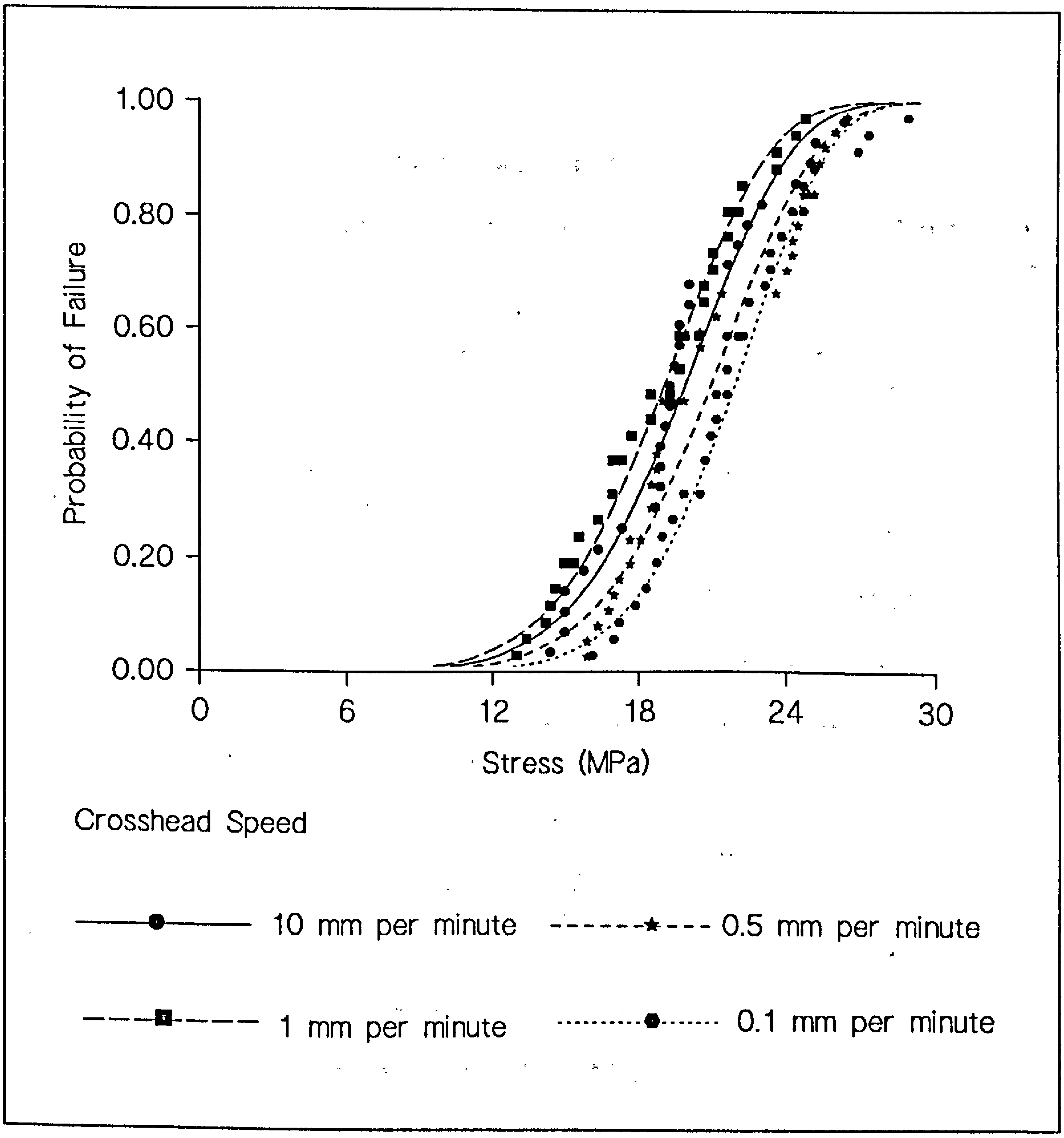


FIGURE 4.3.1.6

Compressive strength of Plaster-Probability of failure versus compressive stress for the specimen size 2 which is tested at various crosshead speeds.

Size 2 = 18mm diameter by 20mm length

TABLE 4.3.1.7

Summary of Weibull Analysis-Compressive strength of Plaster that carried out for specimen size 3 which is tested at various crosshead speeds.

Crosshead Speed (mm/min)	0.1	0.5	1.0	10.0
Weibull Modulus	9.0	10.1	8.8	6.0
Characteristic Strength+	23.1	23.1	23.7	22.5
Standard Error of Modulus	0.54	0.31	0.16	0.10
Coeff. of Correlation	0.98	0.97	0.99	0.99
Mean Strength+	21.9	22.0	22.4	20.9
Deviation Coefficient (%)	11.9	10.8	12.2	17.7
Stress+ at Failure Probability				
0.01% - Weibull	8.5	9.3	8.3	4.8
Normal	20.1	20.4	20.8	18.4
1% - Weibull	14.0	14.6	14.0	10.4
Normal	20.8	21.0	21.4	19.3
99.99% - Weibull	27.3	26.9	28.2	29.0
Normal	23.7	21.6	24.0	23.4

* Size 3 = 18mm diameter by 25mm length.
+ unit in Mpa.
One-way analysis of variance - highly no significant difference between compressive strength and crosshead speed ($P>0.05$).

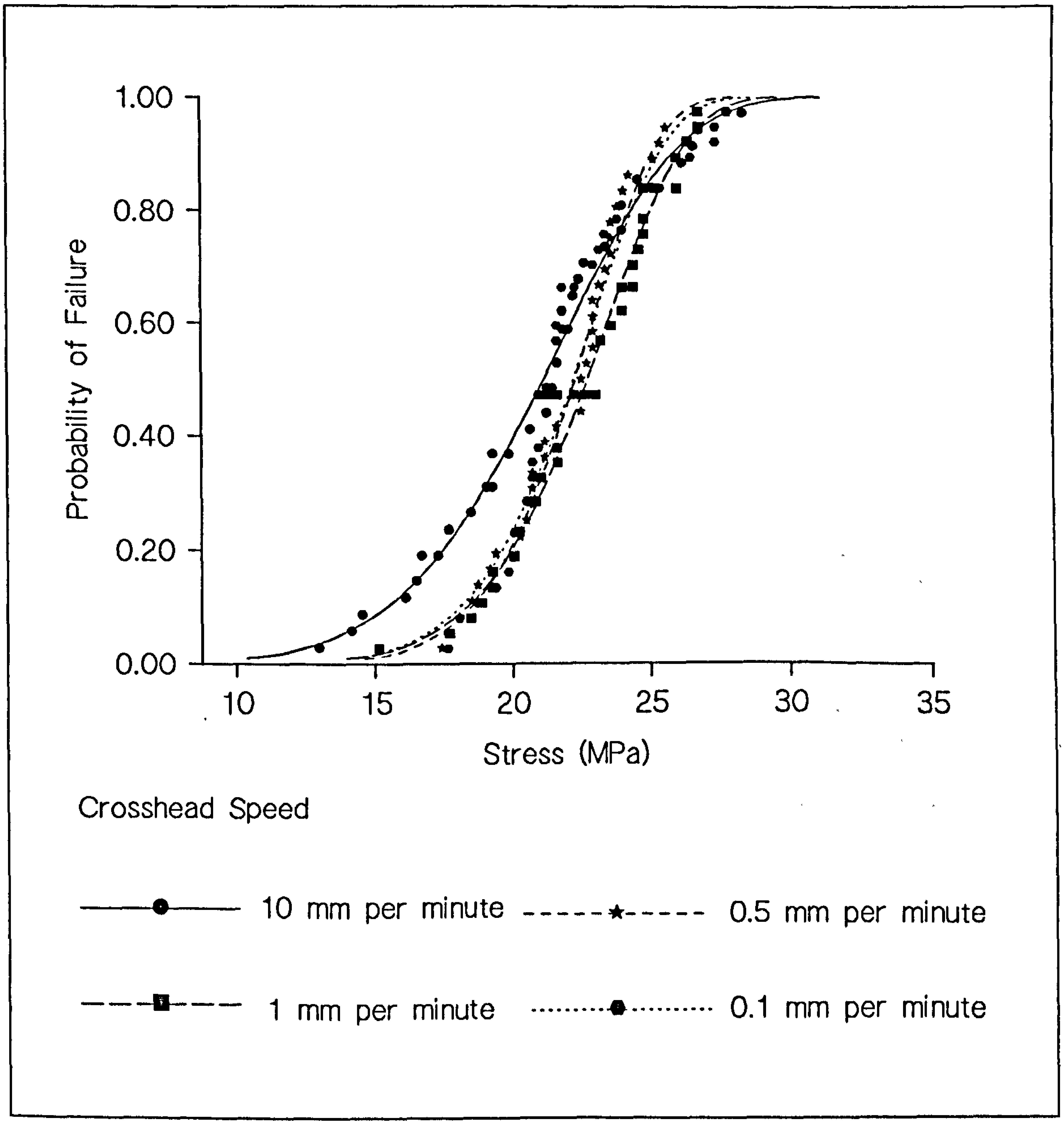


FIGURE 4.3.1.7

Compressive strength of Plaster-Probability of failure versus compressive stress for the specimen size 3 which is tested at various crosshead speeds.

Size 3 = 18mm diameter by 25mm length

TABLE 4.3.1.8

Summary of Weibull Analysis-Compressive strength of Plaster that carried out for specimen size 4* which is tested at various crosshead speeds.

Crosshead Speed (mm/min)	0.1	0.5	1.0	10.0
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	9.1 21.9 0.26 0.97	8.0 21.6 0.42 0.92	6.7 21.0 0.23 0.96	9.5 19.3 0391 0.95
Mean Strength+ Deviation Coefficient (%)	20.8 12.2	20.3 13.0	19.6 16.2	18.3 10.8
Stress+ at Failure Probability				
0.01% - Weibull Normal	7.9 19.2	6.8 17.6	5.3 17.5	7.3 17.0
1% - Weibull Normal	13.2 19.8	12.1 18.6	10.5 21.0	11.9 19.1
99% - Weibull Normal	26.0 22.4	26.1 23.0	26.4 21.7	22.6 19.6

* Size 4 = 18mm diameter by 30mm length.
+unit in Mpa.
One-way analysis of variance- very highly significant difference between compressive strength and crosshead speed (P<0.001).

4 3.1.8

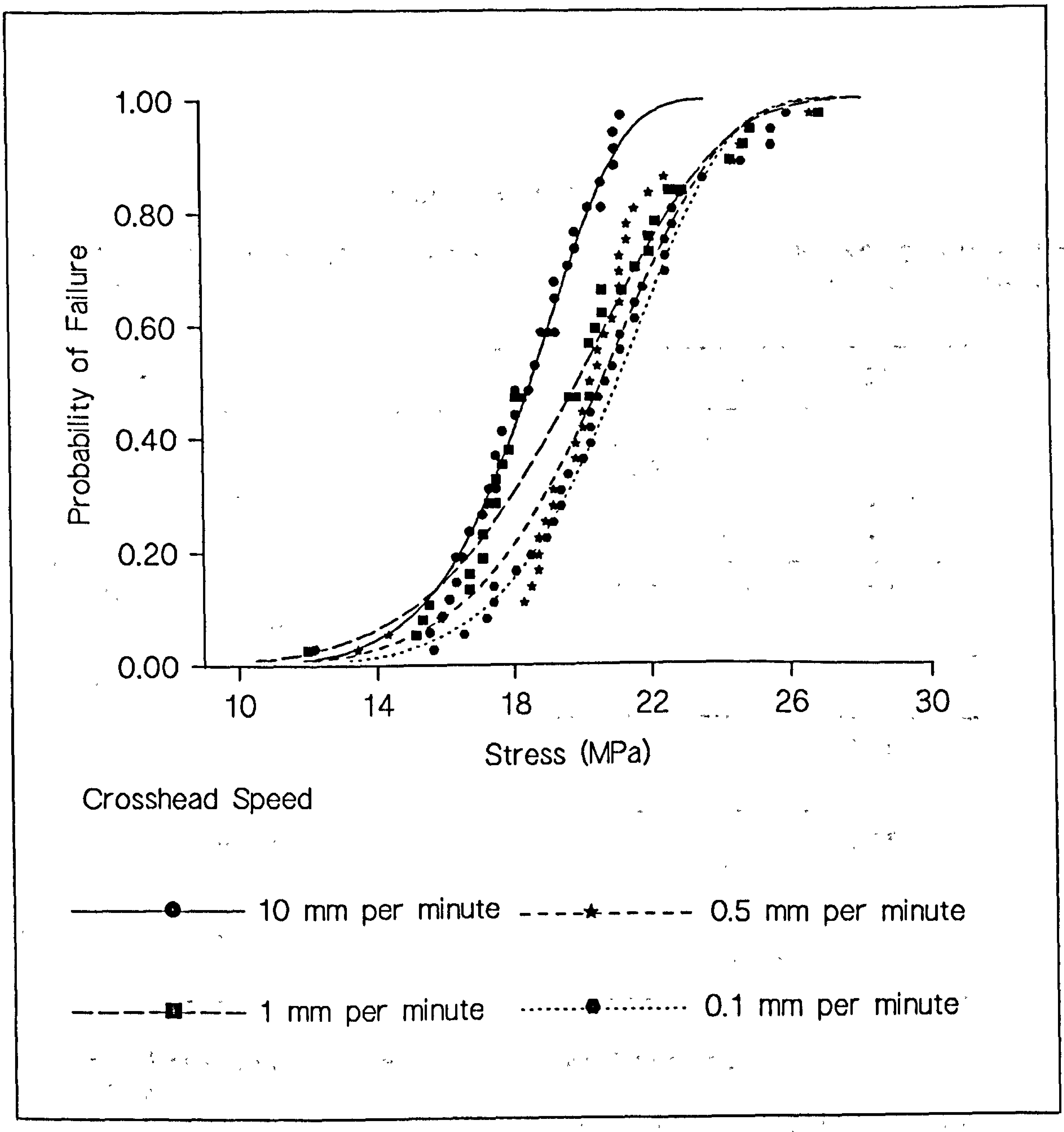


FIGURE 4.3.1.8

Compressive strength of Plaster-Probability of failure versus compressive stress for the specimen size 4 which is tested at various crosshead speeds.

Size 4 = 18mm diameter by 30mm length

TABLE 4.3.2.1

Summary of Weibull analysis-Compressive strength of Opalux for the specimens Diameter/Length ratio of 1:2 * which were tested at various crosshead speed.

Crosshead Speed (mm/min)	0.1	0.5	1	10
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	15.1 284.1 0.85 0.92	15.9 283.9 1.15 0.88	10.0 296.9 0.48 0.94	15.2 304.5 0.59 0.96
Mean Strength+ Deviation Coefficient (%)	274.9 6.7	275.1 6.2	282.2 10.5	294.7 7.1
Stress+ at Failure Probability				
0.01% - Weibull Normal	154.6 262.5	158.9 263.5	118.7 262.2	166.2 262.2
1% - Weibull Normal	209.6 267.1	212.5 267.8	187.6 269.6	255.1 269.6
99.9% - Weibull Normal	314.3 287.3	312.6 286.6	345.7 302.2	336.6 302.2

* Specimen size-2.5mm diameter by 5mm Length.
\+ unit in Mpa.
One-way analysis of variance-Highly significant difference between strength and crosshead speed (P<0.01).

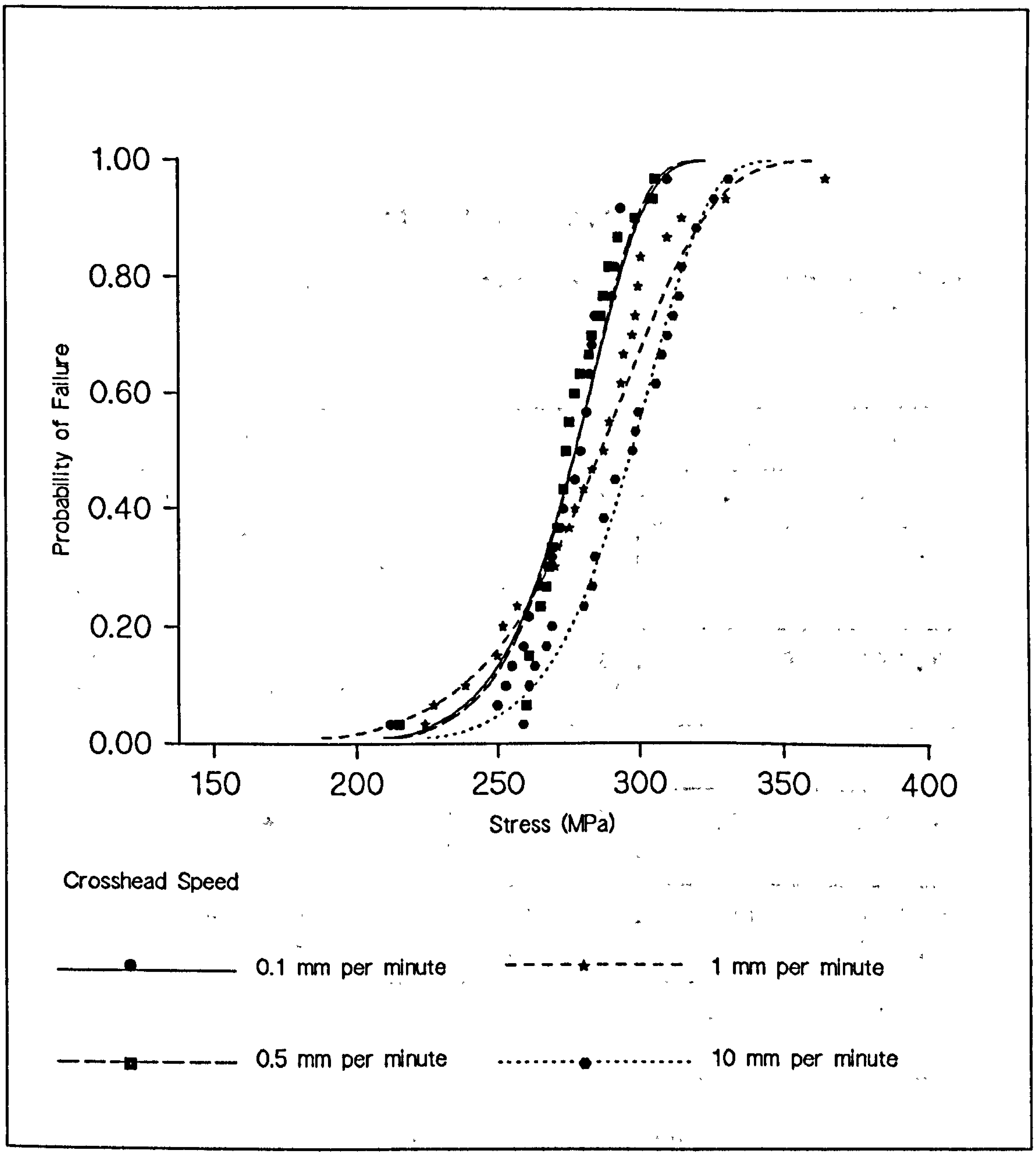


FIGURE 4.3.2.1

Compressive strength of Opalux-Probability of failure versus Compressive stress for the specimens Diameter/Length ratio 1:2 which were tested at various crosshead speed.

Specimen size-2.5mm diameter by 5mm Length.

TABLE 4.3.2.2

Summary of Weibull analysis-Compressive strength of Opalux for the specimens Diameter/Length ratio of 1:2 * which were tested at various crosshead speed.

Crosshead Speed (mm/min)	0.1	0.5	1	10
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	15.2 240.0 0.51 0.97	18.0 229.5 1.01 0.93	16.3 240.1 0.71 0.95	13.7 240.3 0.43 0.98
Mean Strength+ Deviation Coefficient (%)	232.2 7.1	223.1 5.6	232.9 6.5	231.6 7.9
Stress+ at Failure Probability				
0.01% - Weibull Normal	131.0 221.1	137.9 214.7	136.6 222.7	122.6 222.7
1% - Weibull Normal	177.4 225.2	177.8 217.8	181.2 226.5	171.7 226.5
99.9% - Weibull Normal	265.3 243.3	249.8 231.5	263.6 243.1	268.6 243.1

* Specimen size-3mm diameter by 6mm Length.
\+ unit in Mpa.
One-way analysis of variance-No significant difference between strength and crosshead speed (P>0.05).

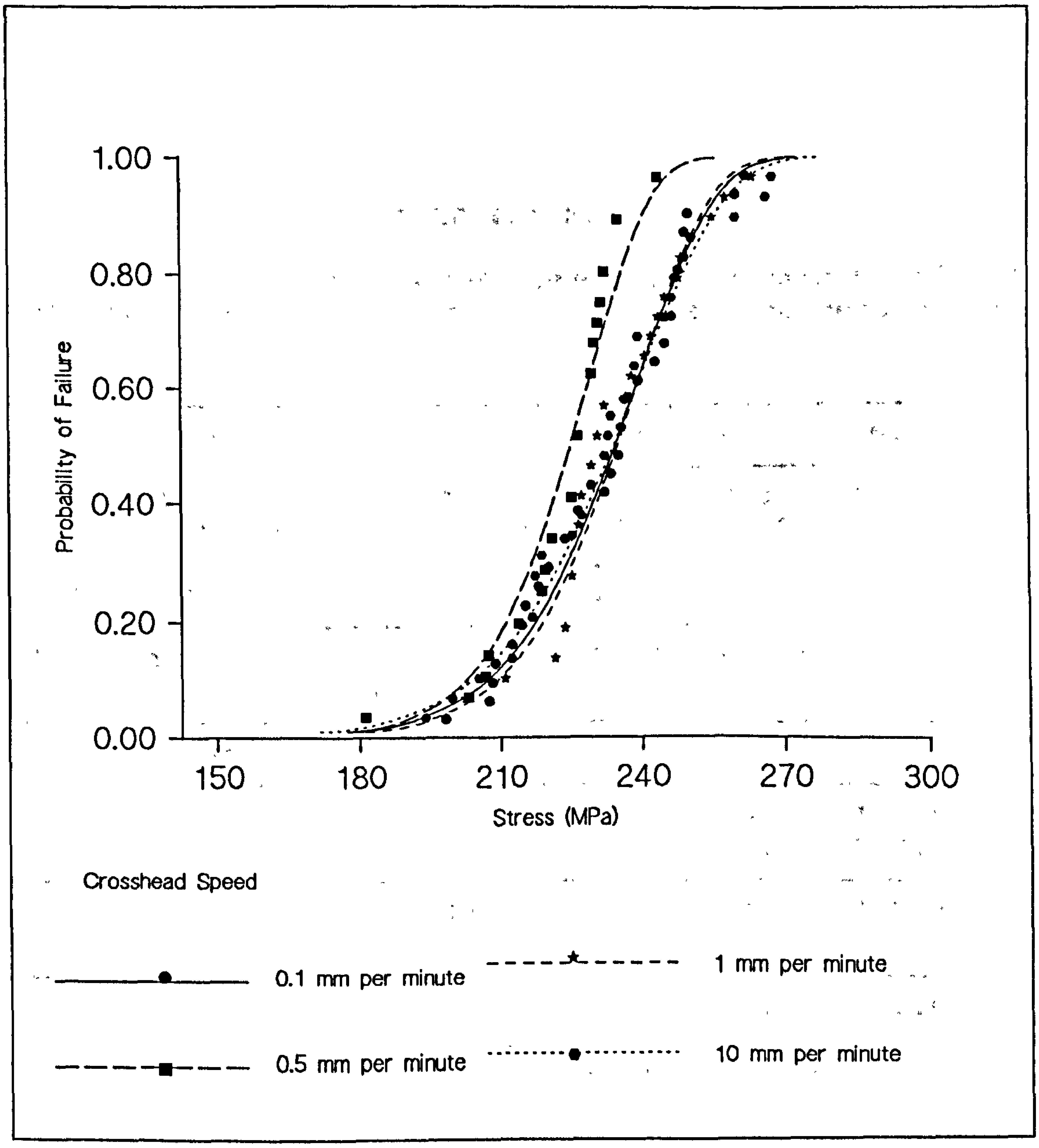


FIGURE 4.3.2.2

Compressive strength of Opalux-Probability of failure versus compressive stress for the specimens of Diameter/Length ratio 1:2 which were tested at various crosshead speed.

Specimen size-3mm diameter by 6mm Length.

TABLE 4.3.2.3

Summary of Weibull analysis-Compressive strength of Opalux tested at crosshead speed 0.1mm/min for the specimens of various diameter size*.

Specimen Diameter (mm)	2.0	3.0	4.0	6.0
Weibull Modulus	10.3	14.4	10.3	11.0
Characteristic Strength+	287.8	227.3	256.90	254.3
Standard Error of Modulus	0.25	0.39	0.47	0.44
Coeff. of Correlation	0.98	0.98	0.95	0.96
Mean Strength+	274.8	219.7	245.14	243.4
Deviation Coefficient (%)	10.3	7.4	9.9	9.3
Stress+ at Failure Probability				
0.01% - Weibull	117.7	119.9	104.7	110.5
Normal	225.7	208.7	228.8	228.75
1% - Weibull	184.1	165.2	164.1	167.7
Normal	262.8	212.9	234.8	234.8
99.9% - Weibull	333.9	252.8	298.1	292.0
Normal	293.9	230.7	261.5	261.5

* Specimen length 4mm.
\+ unit in Mpa.
One-way analysis of variance-Significant difference between strength and specimen diameter (P<0.001).

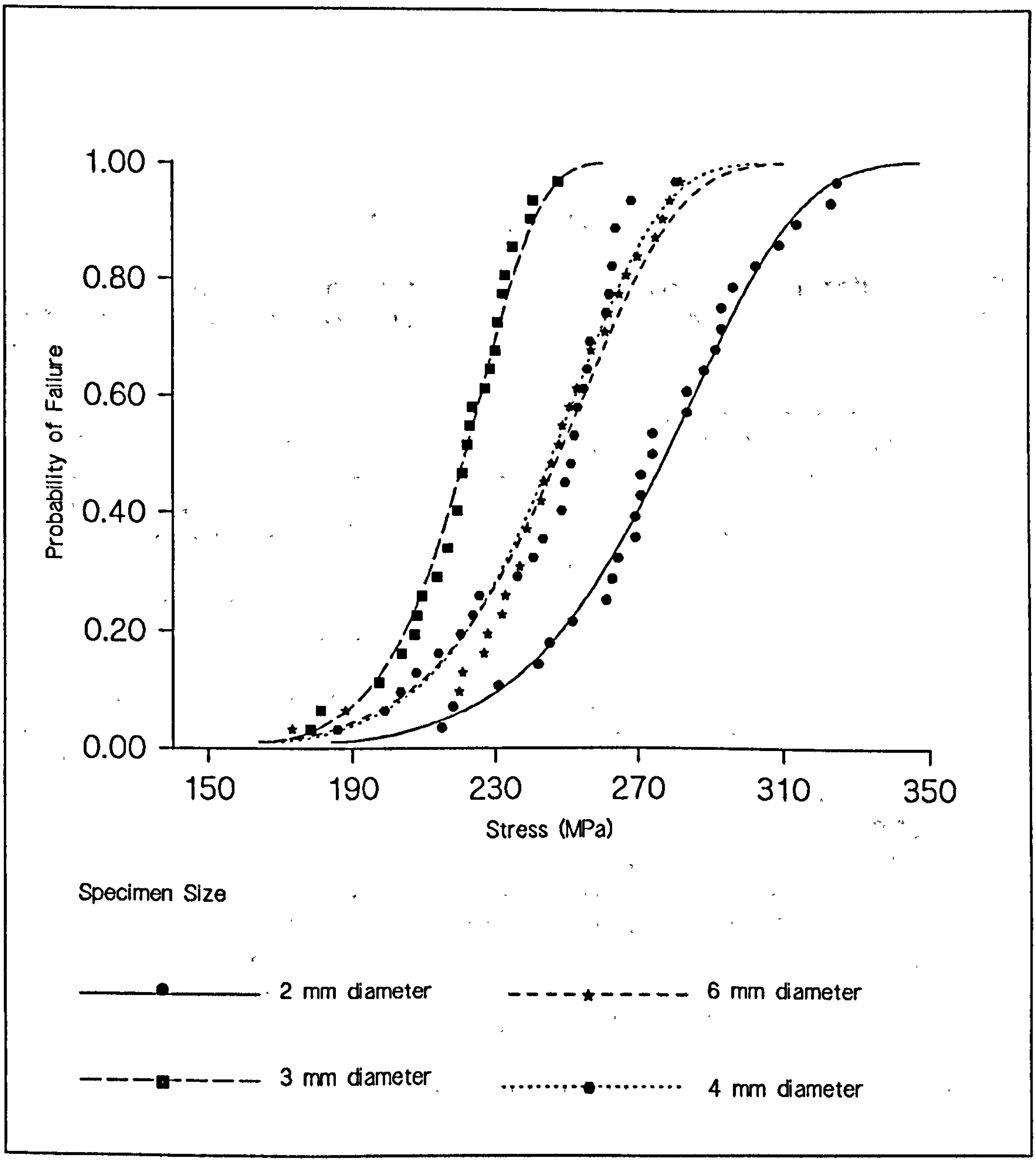


FIGURE 4.3.2.3

Compressive Strength of Opalux-Probability of Failure Versus Compressive Stress Tested at Crosshead Speed 0.1mm/min For Various Diameter Size.

Specimen length = 4mm

TABLE 4.3.2.4

Summary of Weibull analysis-Compressive strength of Opalux tested at crosshead speed 0.1mm/min for the specimens of various diameter sizes*.

Specimen Diameter (mm)		2.5	3.0	4.0	6.0
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation		15.1 284.1 0.85 0.92	15.3 230.5 0.34 0.99	18.3 247.1 0.61 0.97	14.3 242.0 0.49 0.97
Mean Strength+ Deviation Coefficient (%)		274.9 6.7	223.1 7.1	240.4 5.9	234.2 7.5
Stress+ at Failure Probability					
0.01%	- Weibull Normal	154.6 262.5	126.1 221.0	149.2 230.8	127.2 230.8
1%	- Weibull Normal	209.6 267.1	170.5 225.1	192.2 234.4	175.7 234.4
99.9%	- Weibull Normal	314.3 287.3	254.7 243.2	268.6 250.0	269.8 250.0

* Specimen length 5mm.
\+ unit in Mpa.
One-way analysis of variance-Significant difference between strength and specimen diameter (P<0.001).

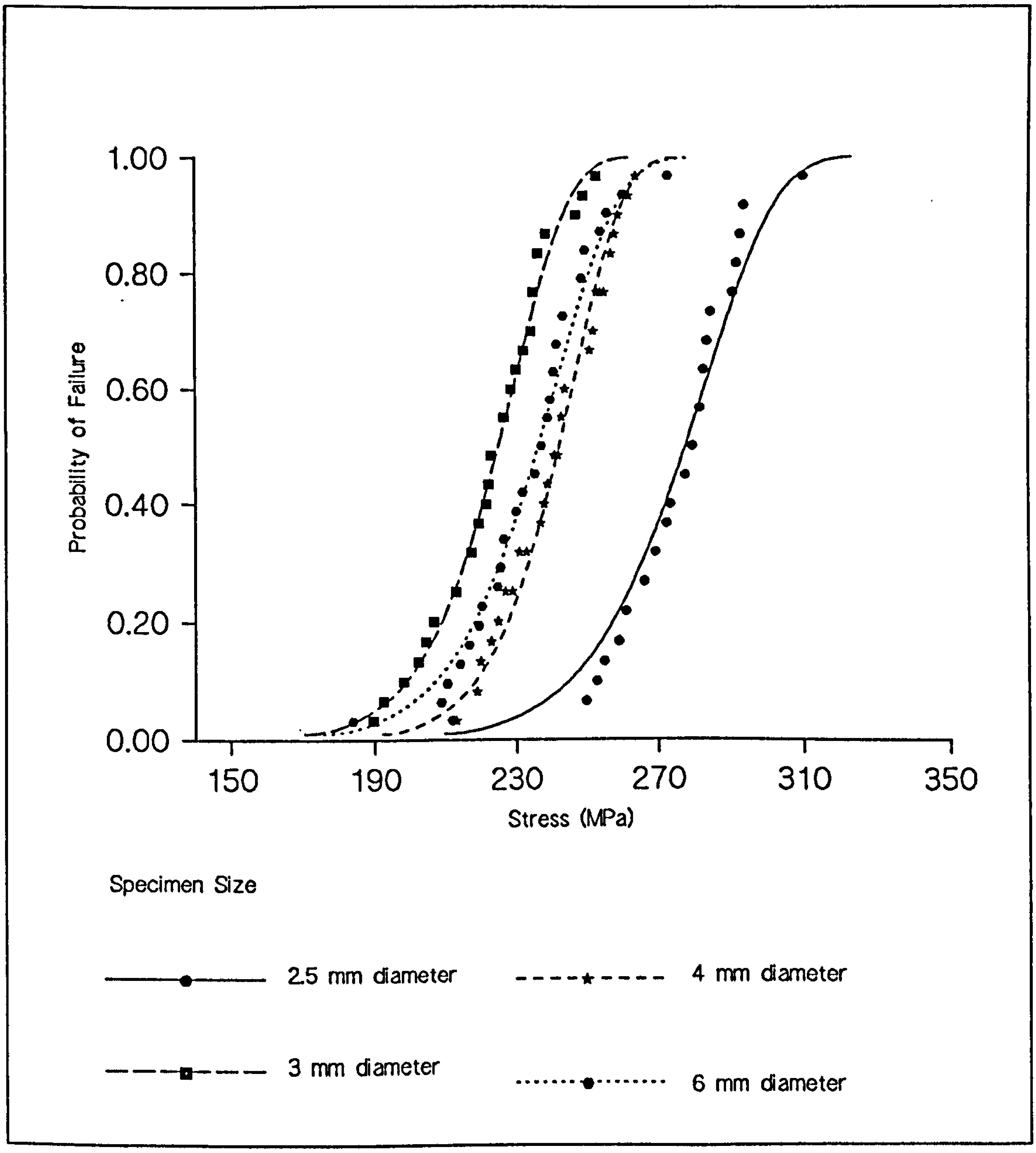


FIGURE 4.3.2.4

Compressive strength of Opalux-Probability of failure versus compressive stress tested at crosshead speed 0.1 mm/min for various diameter Sizes.

Specimen length 5mm.

TABLE 4.3.2.5

Summary of Weibull Analysis-Compressive Strength of Opalux Tested at Crosshead Speed 0.1mm/min for Specimen of Various Diameter Size*.

Specimen Diameter (mm)	3.0	4.0	5.0
Weibull Modulus	15.2	15.6	16.8
Characteristic Strength+	240.0	240.8	245.3
Standard Error of Modulus	0.51	0.57	0.87
Coeff. of Correlation	0.97	0.96	0.93
Mean Strength+	232.2	223.2	238.1
Deviation Coefficient (%)	7.1	6.8	6.1
Stress+ at Failure Probability			
0.01% - Weibull	131.0	133.5	141.6
Normal	221.1	212.9	228.3
1% - Weibull	177.4	179.3	186.5
Normal	225.2	216.7	231.9
99.9% - Weibull	265.3	265.5	268.7
Normal	243.3	233.5	247.9

* Specimen length 6mm.
\+ unit in Mpa.
One-way analysis of variance-No Significant difference between strength and specimen diameter (P>0.05).

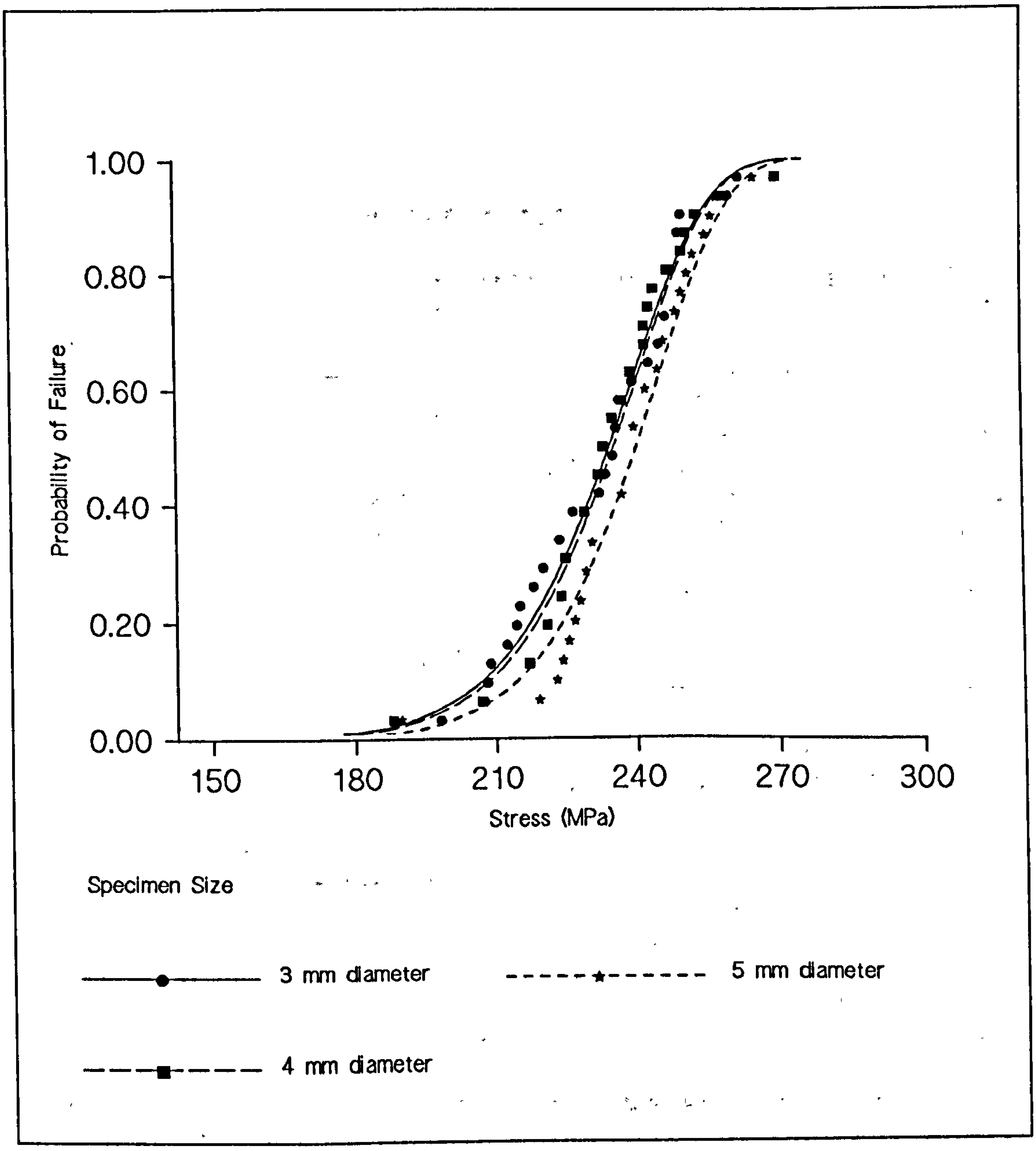


FIGURE 4.3.2.5

Compressive strength of Opalux-Probability of failure versus compressive stress tested at crosshead speed 0.1 mm/min for the specimens various diameter Sizes.

Specimen length 6mm.

TABLE 4.3.3.1

Summary of Weibull Analysis-Compressive Strength of Occlusin Tested at Various Crosshead Speed for Specimen Size 4mm Diameter by 6mm Length*.

Crosshead Speed (mm/min)	10.0	1.0	0.5	0.1
Weibull Modulus	7.7	9.5	13.8	12.5
Characteristic Strength+	233.0	227.6	230.3	206.8
Standard Error of Modulus	0.31	0.73	0.49	0.25
Coeff. of Correlation	0.97	0.86	0.98	0.99
Mean Strength+	219.4	216.3	222.2	198.8
Deviation Coefficient (%)	12.9	9.6	7.5	8.6
Stress+ at Failure Probability				
0.01% - Weibull	70.4	86.3	118.2	99.0
Normal	200.3	202.3	210.9	187.3
1% - Weibull	128.2	140.3	165.0	142.9
Normal	207.4	207.5	215.1	191.5
99% - Weibull	284.2	267.2	257.3	225.8
Normal	238.5	230.3	233.5	210.3

* Specimens were stored in distil water for 7 days at 37°C and at 100% humidity prior testing. One-way analysis of variance-Very highly significant difference between strength and crosshead speed (P<0.001).
+ unit in Mpa.

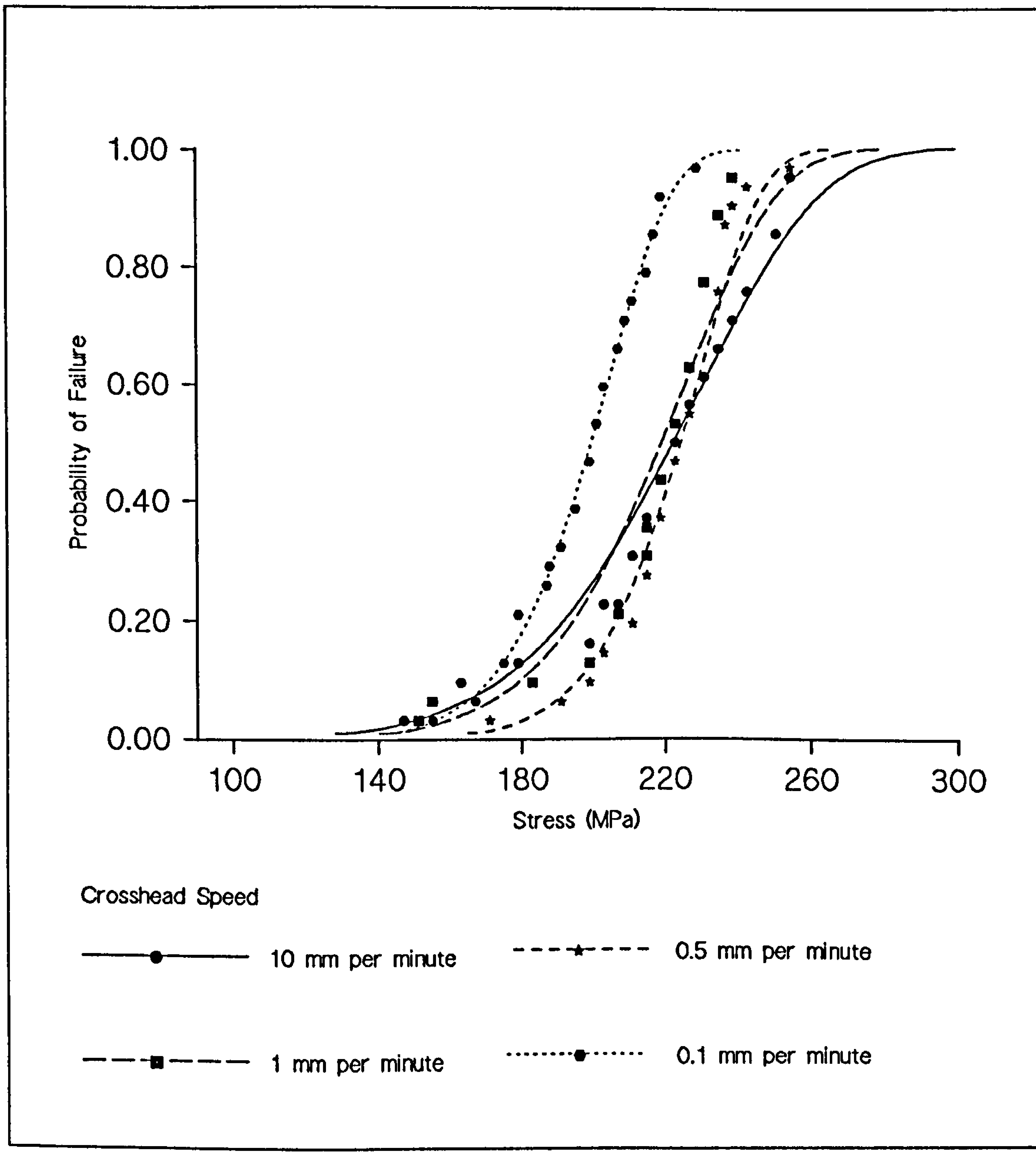


FIGURE 4.3.3.1

Compressive strength of Occlusin-Probability of failure versus compressive stress for the specimens of 4mm diameter by 6mm length which are tested at various crosshead speed.

Specimens are stored in distill water for 7 days at 37°C and at 100% humidity prior testing.

TABLE 4.3.3.2

Summary of Weibull Analysis-Compressive Strength of Occlusin Tested at Various Crosshead Speed for Specimen Size 5mm Diameter by 6mm Length*.

Crosshead Speed (mm/min)	10.0	1.0	0.5	0.1
Weibull Modulus	13.9	10.1	10.4	7.2
Characteristic Strength+	261.0	245.1	233.8	227.1
Standard Error of Modulus	0.40	0.33	0.33	0.13
Coeff. of Correlation	0.98	0.97	0.97	0.99
Mean Strength+	248.1	232.7	223.2	213.1
Deviation Coefficient (%)	12.2	11.9	9.9	14.6
Stress+ at Failure Probability				
0.01% - Weibull	134.5	98.5	96.4	63.2
Normal	227.6	214.0	208.3	192.1
1% - Weibull	187.3	155.3	150.2	119.4
Normal	235.2	220.9	213.8	199.9
99.9% - Weibull	291.4	285.2	270.8	281.1
Normal	268.5	251.4	238.1	234.1

* Specimens were stored in distil water for 7 days at 37°C and at 100% humidity prior testing. One-way analysis of variance-Very highly significant difference between strength and crosshead speed ($P<0.001$).
\+ unit in Mpa.

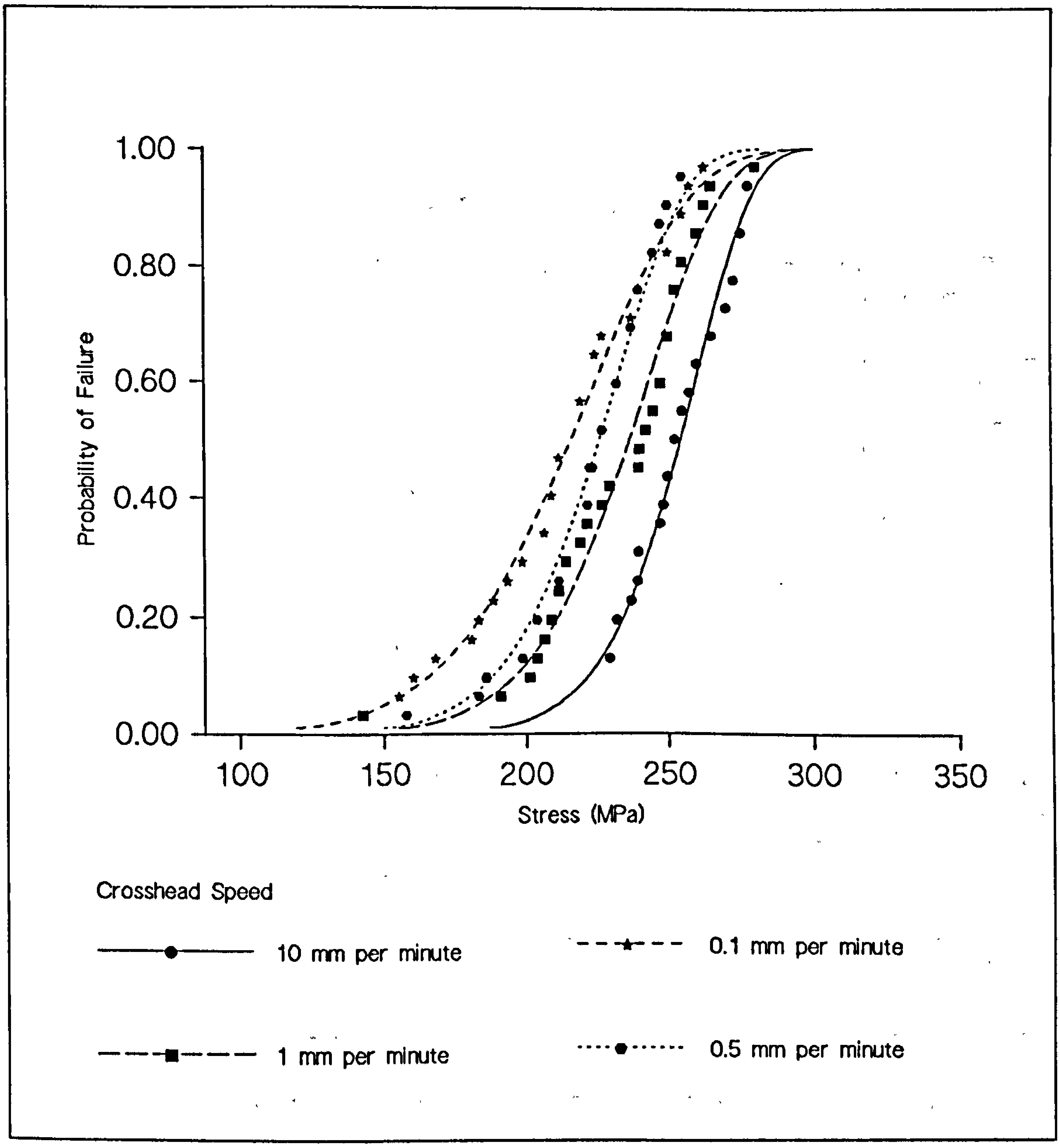


FIGURE 4.3.3.2
Compressive strength of Occlusin-Probability of failure versus compressive stress for the specimens of 5mm diameter by 6mm length which are tested at various crosshead speed.
Specimens are stored in distill water for 7 days at 37°C and at 100% humidity prior testing.

TABLE 4.3.3.3

Summary of Weibull Analysis-Compressive Strength of Occlusin Tested at Various Crosshead Speed for Specimen Size 6mm Diameter by 6mm Length*.

Crosshead Speed (mm/min)	10.0	1.0	0.5	0.1
Weibull Modulus	6.4	6.1	6.8	9.2
Characteristic Strength+	245.8	246.2	252.6	234.4
Standard Error of Modulus	0.38	0.34	0.34	0.58
Coeff. of Correlation	0.91	0.92	0.93	0.91
Mean Strength+	229.3	229.0	236.1	222.5
Deviation Coefficient (%)	16.9	17.0	14.0	10.3
Stress+ at Failure Probability				
0.01% - Weibull	58.3	54.4	65.2	86.12
Normal	203.1	202.7	213.8	207.0
1% - Weibull	120.3	116.4	127.9	142.2
Normal	212.8	212.4	222.0	212.8
99.99% - Weibull	311.6	315.7	316.8	264.1
Normal	255.5	255.3	258.4	238.0

* Specimens were stored in distil water for 7 days at 37°C and at 100% humidity prior testing. One-way analysis of variance-Very highly significant difference between strength and crosshead speed (P>0.5).
\+ unit in Mpa.

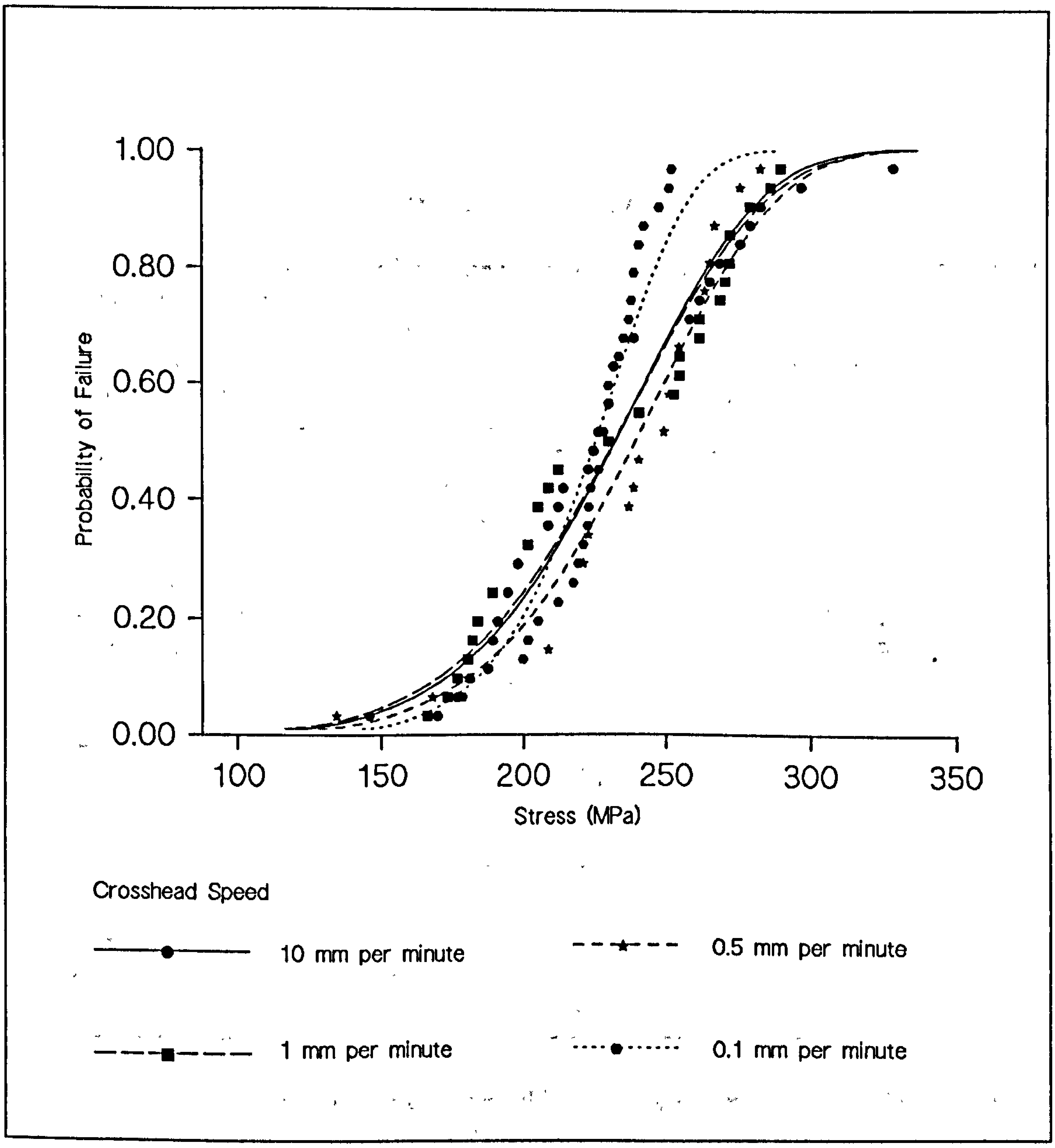


FIGURE 4.3.3.3

Compressive strength of Occlusin-Probability of failure versus compressive stress for the specimens of 6mm diameter by 6mm length which are tested at various crosshead speed.

Specimens are stored in distill water for 7 days at 37°C and at 100% humidity prior testing.

TABLE 4.3.3.4

Summary of Weibull analysis-Compressive strength of Occlusin for the specimens of various diameter size (of 6mm length) which were tested at crosshead speed 10mm/min.

Diameter (mm)		4.0	5.0	6.0
Weibull Modulus		7.7	13.9	6.4
Characteristic Strength+		233.0	261.0	245.8
Standard Error of Modulus		0.31	0.40	0.38
Coeff. of Correlation		0.97	0.98	0.91
Mean Strength+		219.4	248.1	229.3
Deviation Coefficient (%)		12.9	12.2	16.9
Stress+ at Failure Probability				
0.01%	- Weibull	70.4	134.5	58.3
	Normal	200.3	227.6	203.1
1%	- Weibull	126.2	187.3	120.3
	Normal	207.4	235.2	212.8
99.9%	- Weibull	284.2	291.4	311.6
	Normal	238.5	268.6	255.5

+ unit In Mpa.
* Specimens were stored in distil water for 7 days at 37°C and at 100% humidity prior testing.
One-way analysis of variance-Highly significant difference between strength and specimen size ($P<0.01$).

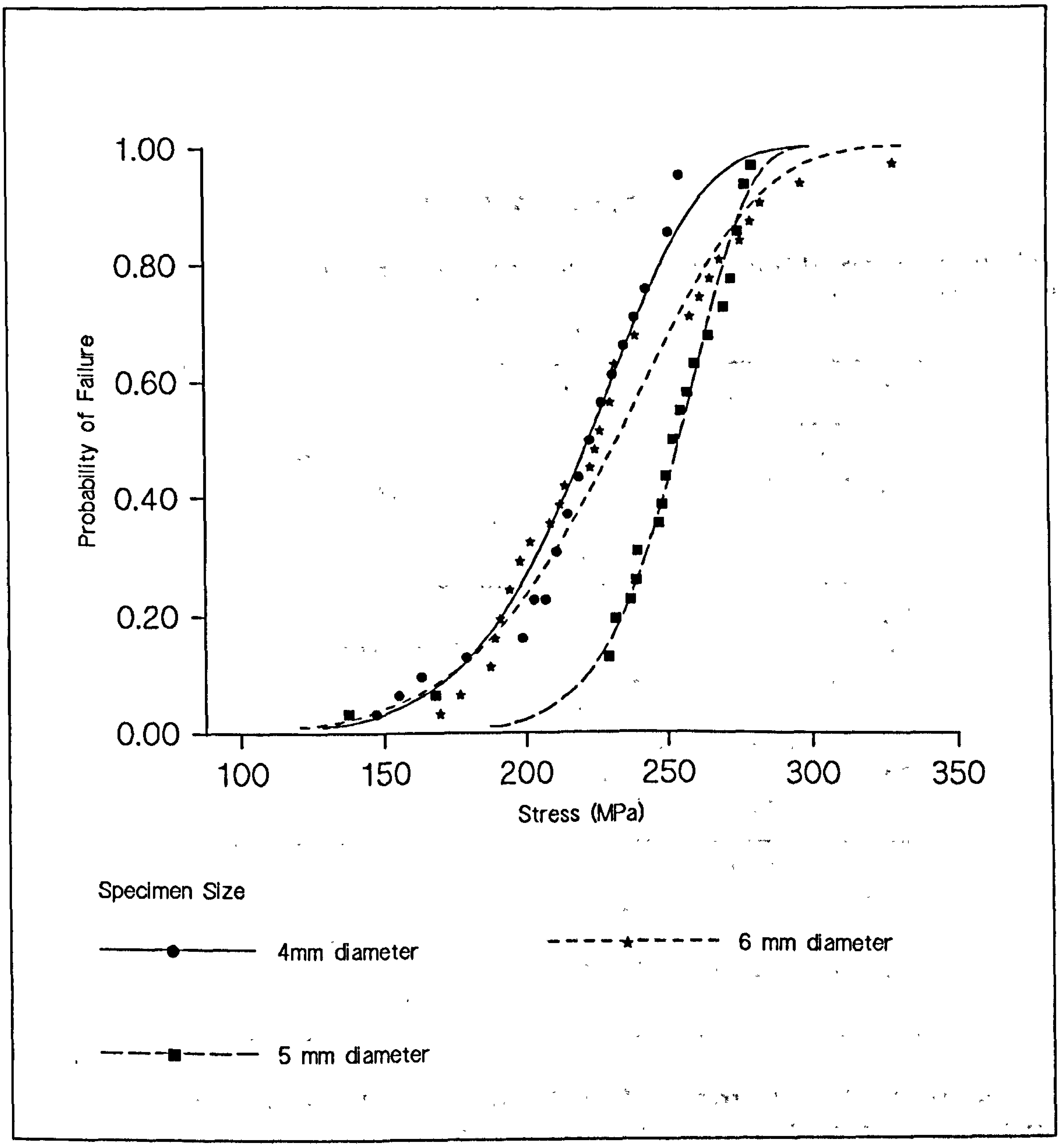


FIGURE 4.3.3.4

Compressive strength of Occlusin-Probability of failure versus compressive stress for the specimens of various diameter size (of 6mm length) which are tested at crosshead speed 10mm/min.

Specimens are stored in distill water for 7 days at 37°C and at 100% humidity prior testing.

TABLE 4.3.3.5

Summary of Weibull analysis-Compressive strength of Occlusin for th specimens of various diameter size (of 6mm length) which were tested at crosshead speed 1mm/min.

Diameter (mm)	4.0	5.0	6.0
Weibull Modulus	9.5	10.1	6.1
Characteristic Strength+	227.6	245.1	246.2
Standard Error of Modulus	0.73	0.33	0.34
Coeff. of Correlation	0.86	0.97	0.92
Mean Strength+	216.3	232.7	229.0
Deviation Coefficient (%)	9.6	11.9	17.0
Stress+ at Failure Probability			
0.01% - Weibull	70.4	98.5	54.40
Normal	202.3	214.0	202.7
1% - Weibull	140.4	155.3	116.4
Normal	207.5	220.9	212.4
99.9% - Weibull	267.2	285.2	315.7
Normal	230.3	251.4	255.3

+ unit in Mpa.
* Specimens were stored in distil water for 7 days at 37°C and at 100% humidity prior testing. One-way analysis of variance-No significant difference between strength and specimen size (P>0.05).

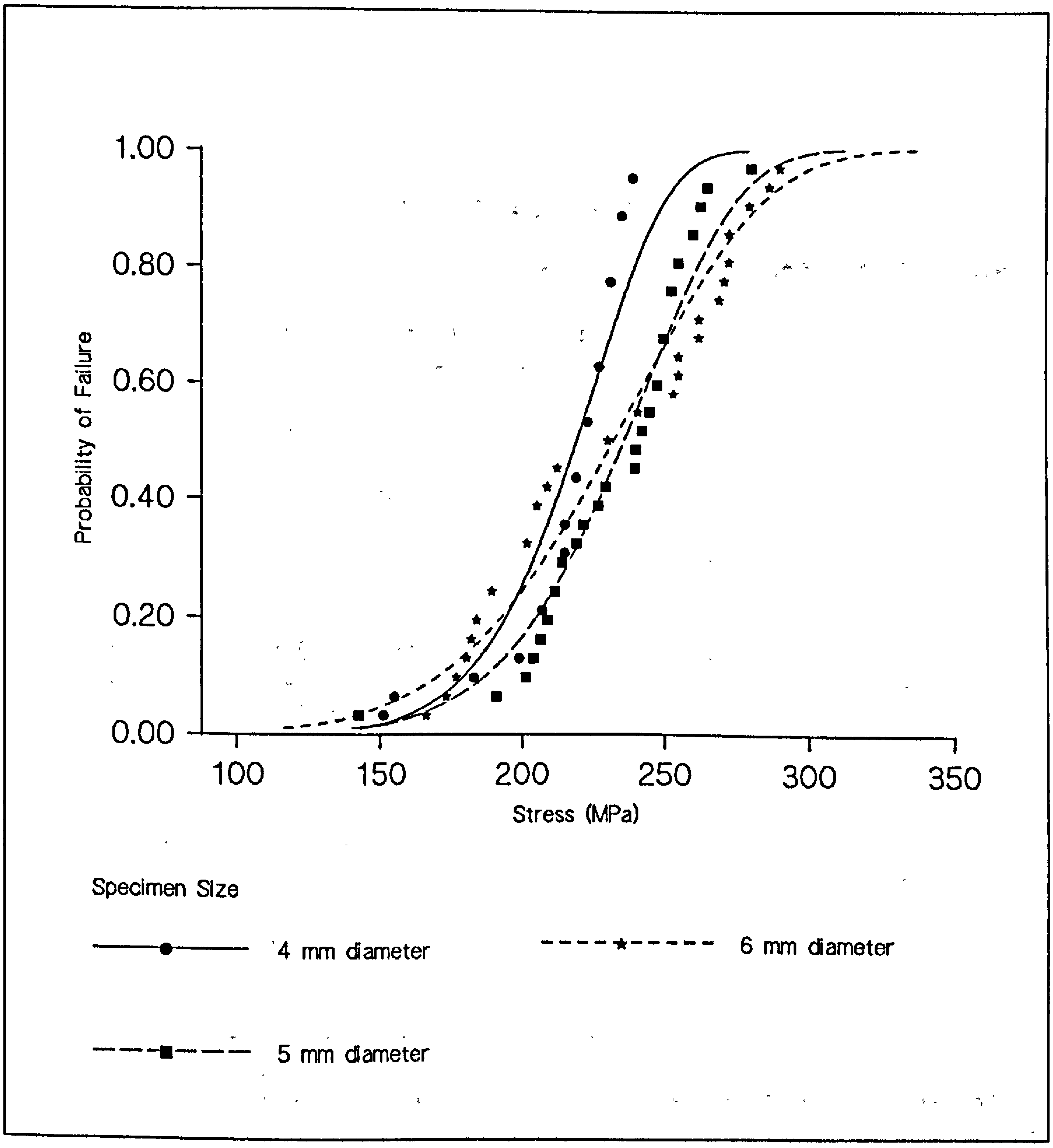


FIGURE 4.3.3.5
Compressive strength of Occlusin-Probability of failure versus compressive stress for the specimens of various diameter size (of 6mm length) which are tested at crosshead speed 1mm/min.
Specimens are stored in distill water for 7 days at 37°C and at 100% humidity prior testing.

TABLE 4.3.3.6

Summary of Weibull analysis-Compressive strength of Occlusin for the specimens* of various diameter size (of 6mm length) which were tested at crosshead speed 0.5mm/min.

Diameter (mm)		4.0	5.0	6.0
Weibull Modulus		13.8	10.4	6.8
Characteristic Strength+		230.3	233.8	252.6
Standard Error of Modulus		0.49	0.33	0.35
Coeff. of Correlation		0.97	0.97	0.93
Mean Strength+		222.2	223.2	236.1
Deviation Coefficient (%)		7.5	9.9	14.0
Stress+ at Failure Probability				
0.01%	- Weibull	118.2	96.4	65.20
	Normal	210.9	208.3	213.8
1%	- Weibull	165.0	150.2	127.9
	Normal	215.1	213.8	22.01
99.9%	- Weibull	257.3	270.8	316.7
	Normal	233.5	238.1	258.4

+ unit in Mpa.
* Specimens were stored in distil water for 7 days at 37°C and at 100% humidity prior testing. One-way analysis of variance-Significant difference between strength and specimen size ($P<0.05$).

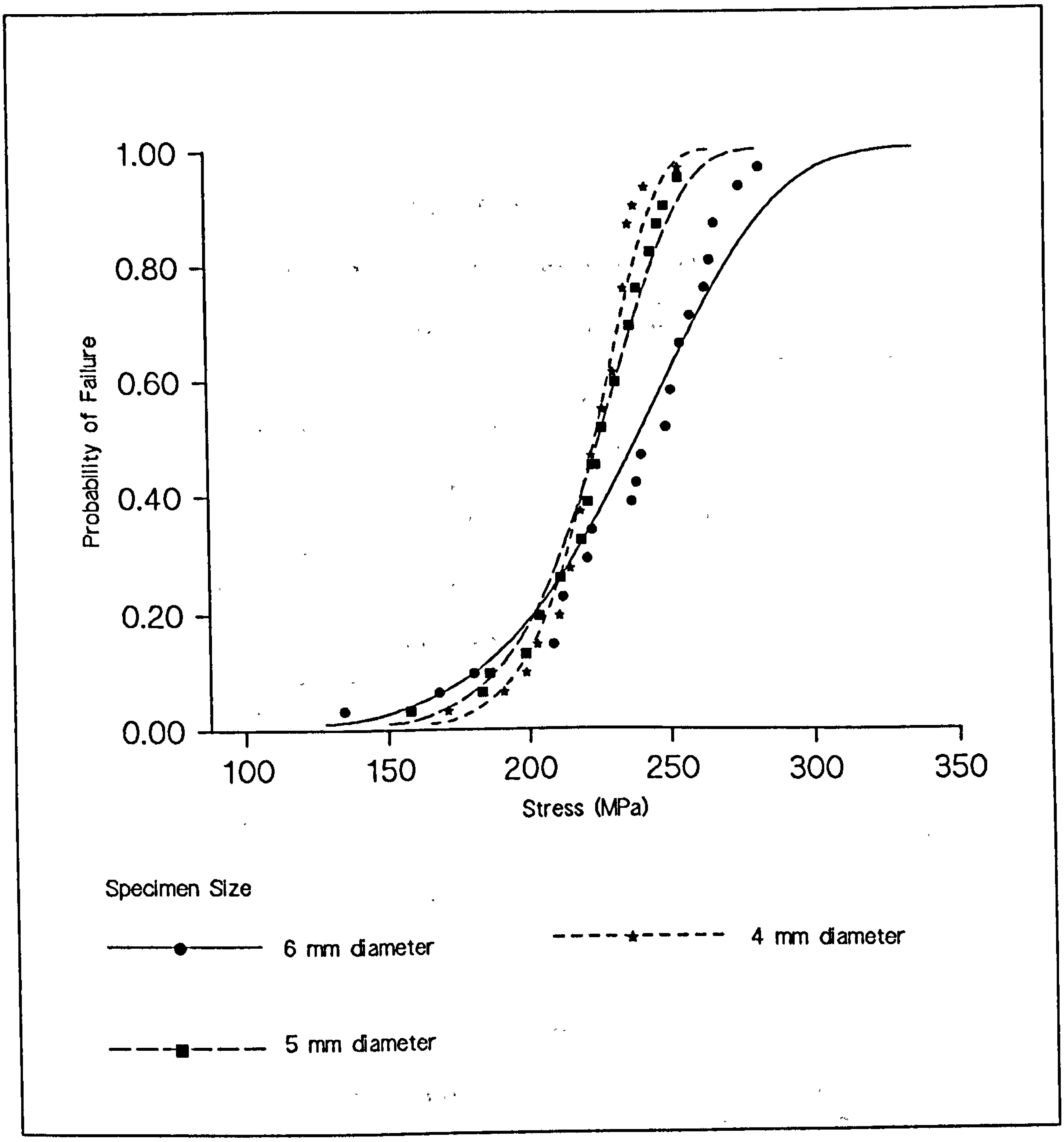


FIGURE 4.3.3.6
Compressive strength of Occlusin-Probability of failure versus compressive stress for the specimens of various diameter size (of 6mm length) which are tested at crosshead speed 0.5mm/min.
Specimens are stored in distill water for 7 days at 37^{o}C and at 100% humidity prior testing.

TABLE 4.3.3.7

Summary of Weibull analysis-Compressive strength of Occlusin for the specimens of various diameter size (of 6mm length) which were tested at crosshead speed 0.1mm/min.

Diameter (mm)		4.0	5.0	6.0
Weibull Modulus		12.5	7.2	9.2
Characteristic Strength+		206.8	227.1	234.4
Standard Error of Modulus		0.25	0.13	0.58
Coeff. of Correlation		0.99	0.99	0.91
Mean Strength+		198.8	213.1	222.5
Deviation Coefficient (%)		8.7	14.6	10.4
Stress+ at Failure Probability				
0.01%	- Weibull	99.00	63.2	86.1
	Normal	187.1	192.1	206.9
1%	- Weibull	143.0	119.4	142.2
	Normal	191.4	199.9	212.6
99.9%	- Weibull	225.8	281.1	264.1
	Normal	210.5	234.1	238.1

+ unit in Mpa.
* Specimens were stored in distil water for 7 days at $37^{o}C$ and at 100% humidity prior testing. One-way analysis of variance-Very highly significant difference between strength and specimen size (P<0.001).

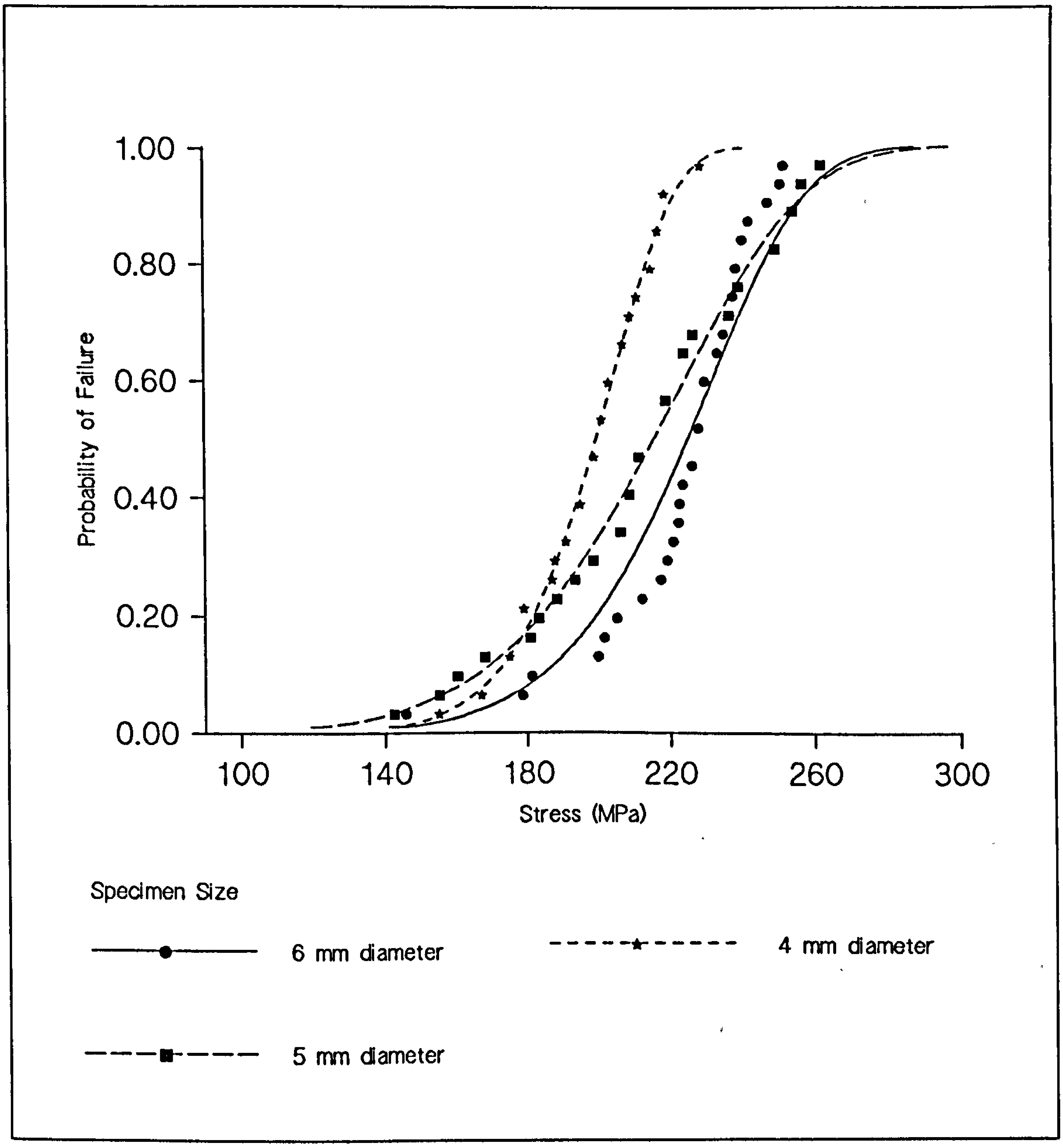


FIGURE 4.3.3.7
Compressive strength of Occlusin-Probability of failure versus compressive stress for the specimens of various diameter size (of 6mm length) which are tested at crosshead speed 0.1mm/min.
Specimens are stored in distill water for 7 days at 37°C and at 100% humidity prior testing.

4.3.1 The Effect of Specimen Size and Crosshead speed on The Compressive Strength of Plaster of Paris

The results for the compressive strength of plaster of paris are tabulated in Tables 4.3.1.1, 4.3.1.2, 4.3.1.3, 4.3.1.4, 4.3.1.5, 4.3.1.6, 4.3.1.7 and 4.3.1.8 . They show a summary of the analysis of the Weibull distribution and the Normal distribution. Figures 4.3.1.1, 4.3.1.2, 4.3.1.3, 4.3.1.4, 4.3.1.5, 4.3.1.6, 4.3.1.7 and 4.3.1.8 show a graphical representation of the results from the Weibull distribution analysis.

For the Normal statistic, an analysis of variance is used to analyse the data. An analysis of variance (ANOVA) showed that there was a very highly significant variation in the mean compressive strength of Plaster of Paris with specimen sizes and with crosshead speeds ($P < 0.001$). Two-way interaction between specimen size and crosshead speed showed that there was a highly significant difference ($P < 0.01$). This evidently shows that specimen size and the crosshead speed of testing affect the mean compressive strength of Plaster of Paris.

One-way analyses of variance have been carried out to analyse the effect of the specimen size on the mean compressive strength of Plaster of Paris when tested at each crosshead speed. The analysis has showed that there was a significant difference between the mean compressive strength of Plaster of Paris of various specimen sizes when the test was performed at crosshead speeds of 1 and 10 mm per minute (P<0.05). There was a highly significant difference between the mean compressive strength of Plaster of Paris of various specimen sizes when the test was carried out at crosshead speed of 0.5 mm per minute (P<0.01). However, there was highly no significant difference between the mean compressive strength of Plaster of Paris of various specimen sizes when the test carried out at a crosshead speed of 0.1 mm per minute (P=0.55). Thus this means that the test carried out at crosshead speed 0.1 mm per minute does not affect the mean compressive strength of Plaster of Paris for all the specimen sizes tested. Table 4.3.1.4 shows the results for the compressive strength of Plaster of Paris for the specimen sizes 1-4 when tested with a crosshead speed 0.1 mm per minute. The mean strength and the percentage of deviation coefficient (coefficient of variation) for all the specimen sizes are very close to each other particularly for specimen sizes 1-3. A slow crosshead speed produces a slow rate of strain, thus a crack's Propogation ~~propogatation~~ from a flaw in the specimen is also slow. The failure may occur when the most critical flaw is being initiated. For some brittle materials particularly for polymeric materials, local elastic and plastic deformation may influence the mode of failure (Darvell:1990). This behaviour may also be the result of a slow strain rate. However this is not the case for high strain rate. The failure of the specimen may not because of the most critical flaw is being initiated. The results of the tests that have been carried out at a crosshead speed of 10 mm per minute are shown in Table 4.3.1.1. There is a significant difference between the mean strengths with varying specimen size ($p<0.05$). The Tukey range test shows that the mean strength of the specimens of sizes 18 mm diameter by 15 mm length, 18 mm diameter by 20 mm length and 18 mm diameter by 25 mm length are not significantly different ($p>0.05$). This may be due to the fact that their modes of failure are exactly the same. The specimens fail by spallation, that is by double-wedge shaped pieces separating from the sizes (Trollope and Brown:1966) as the diameter/length ratio of the specimens is greater than 1:2 (Robert:1985, Sigvaldason:1964). The mean strengths of these specimens are higher than the mean strength of the specimens of size 18 mm diameter by 30 mm length. This is because a complex stress distribution is formed as a result of overlapping of shear stress (Robert:1985).

The results for the tests that have been carried out at a crosshead of 1 mm per minute are shown in Table 4.3.1.2 and Figure 4.3.1.2. Figure 4.3.1.2 shows that there are two groups of Weibull curve plotted. The Weibull curves of the specimen sizes 18 mm diameter by 15 mm length and 18 mm diameter by 20 mm length are formed one group and specimen size 18 mm diameter by 25 mm length and 18 mm diameter by 30 mm length are formed another groups. This shows that the strength of the specimen sizes 18 mm diameter by 15 mm length and 18 mm diameter by 20 mm length are the same, and the specimen sizes 18 mm diameter by 25 mm length and 18 mm diameter by 30 mm length are the same. The Tukey range test shows that the mean strengths of the specimens of sizes 18 mm diameter by 15 mm length and 18 mm diameter by 20 mm length are not significantly different ($p>0.05$) This is also true for the other group of specimen sizes. The behaviour of these results is approximately the same as discussed in the previous paragraph, except the complex stress due to the overlapping of stress is not so significant in the specimen size 18 mm diameter by 25 mm length when a crosshead speed of 1 mm per minute is used. This effect can also be seen for the tests that have been carried out at a crosshead speed of 0.5 mm per minute. The mode of failure for the specimen size 18 mm diameter by 25 mm length and 18 mm diameter by 30 mm length may be because of crack propagation from a critical flaws.

The above results show a crosshead speed of 0.1 mm per minute may be suitable for the compressive test. It also shows that the reliability of the specimen size of diameter/length ratio of approximately 1:2 may be suitable for the compressive test. Another set of tests were carried out to study the effect of crosshead speed on the compressive strength of Plaster of Paris when tested at various specimen sizes. One-way analysis showed that there was no significant variation in the mean compressive strength of Plaster of Paris for varying crosshead speed ($P = 0.15$) when the test was carried out for the specimen size 18 mm diameter by 25 mm length. Further more, the Tukey range test showed there was no significant difference between the value of the mean strength calculated for each crosshead speed. One-way analysis of variance also showed that there was no significant variation in the mean compressive strength of Plaster of Paris for various crosshead speeds (P = 0.11) when the test was carried out on ~~a~~ the specimens of size 18 mm diameter by 15 mm length. However the results for the specimens of size 18 mm diameter by 25 mm length were better than size 18 mm diameter by 15 mm length because the probability of significance level of the specimen size 18 mm diameter by 25 mm length is greater than for the specimen size 18 mm diameter by 15 mm length. This means that the specimens of size 18 mm diameter by 25 mm length do not affect the compressive strength of Plaster of Paris when tested at all crosshead speeds. This may because the diameter/length ratio of the specimens is nearly equal to 1:2 (Robert:1985, Sigvaldason:1964).

Table 4.3.1.7 shows the results for the compressive strength of Plaster of Paris for the specimen size 18 mm diameter by 25 mm length (i.e specimen diameter/depth ratio of 3:4) when tested at crosshead speeds of 0.1, 0.5, 1.0 and 10 mm per minute. The mean strength and the percentage of deviation coefficient (coefficient of variation) for all the specimen sizes are very close to each other particularly for crosshead speeds 0.1, 0.5 and 1.0 mm per minute. This may be due to the plastic behaviour of the specimens when tested at a crosshead speed of 0.1,0.5 and 1 mm per minute. The mode at failure may be characterised by plastic flow (Darvell:1990). At a higher crosshead speed, the mode of failure is catastrophic. This is shown by a lower Weibull modulus, when the test was carried out at a crosshead speed of 10 mm per minute. A low value of Weibull modulus indicates a brittle behaviour of a material, it also explains the scatter within the data. The results may not be reliable when the value of the Weibull modulus is low. Figure 4.3.1.7 shows that the performance of the specimens that have been tested at a crosshead speeds of 0.1 and 0.5 mm per minute is approximately the same. Weibull curves for the specimens of the tests carried out at a crosshead speeds of 0.1 and 0.5 mm per minute are close to each other. This suggests that the specimen size of 18 mm diameter by 25 mm length may give reliable results when either a crosshead speed of 0.1 or 0.5 mm per minute is used. This is in agreement with the results for the tests of the effect of specimen size on compressive strength of Plaster of Paris.

Table 4.3.1.5 shows the results of the specimens of size 18 mm diameter by 15 mm length that have been tested at various crosshead speeds. The mean strength of the specimen at each test is approximately the same. The values of the Weibull modulus for these tests are also approximately the same. The degree of brittleness of the specimens is approximately the same. Figure 4.3.1.5 shows there are two groups of curves plotted. A group of specimens that have been tested at a crosshead speed of 0.1 and 0.5 mm per minute are performed better than that the specimens of the other group. This is because the characteristic strengths and Weibull moduli of the specimens tested at a crosshead speeds of 0.1 and 0.5 mm per minute are higher than the characteristic strengths and Weibull moduli of the specimens of the other group. The difference in compressive strength of the specimens between these groups may be due to the mode of failure. The mode of failure of the specimens that have been tested at a crosshead speed of 0.1 and 0.5 mm per minute may be due to the local elastic and plastic flows (Darvell:1990). A catastrophic failure may be the characteristic mode of failure of the other group. The compressive strength and Weibull modulus are found to be higher for the plastic flow phenomenon when compared to the compressive strength and Weibull modulus of the specimens that have been fractured by catastrophic failure. Therefore performances of the specimens failing by the plastic flow phenomenon are better than the performances of the specimens that have been fractured by catastrophic failure. This shows that the specimen size of 18 mm diameter by 15 mm length may give more reliable results when a crosshead speed of either 0.1 mm per minute or 0.5 mm per minute is used. However the significance of the tests of the specimens of size 18 mm diameter by 15 mm length that have been tested at various crosshead speeds is less when compared to the tests of the specimens of size 18 mm diameter by 25 mm length. Nevertheless Table 4.3.1.5 and Figure 4.3.1.5 show the reliability of the crosshead speeds of 0.1 and 0.5 mm per minute. This is also shown in the results of the specimens of size 18 mm diameter by 20 mm length that have been tested at various crosshead speeds. These findings are in agreement with the results for the tests of the effect of specimen size on the compressive strength of Plaster of Paris.

Table 4.3.1.8 shows the results for the specimens of size 18 mm diameter by 30 mm length that have been tested at various crosshead speeds. There is a highly significant difference between the mean strengths for varing crosshead speed ($p<0.001$). However the Tukey range test shows the mean strengths of the specimens tested at a crosshead speeds of 0.1 and 0.5 mm per minute are approximately the same ($p>0.05$). Further more the mean strengths of the specimens for these tests are higher than the mean strengths of the specimens for the tests that have been carried out at crosshead speeds of 1 and 10 mm per minute. The value of Weibull modulus of the specimens for the tests that have been carried out at crosshead speeds 0.1 and 0.5 mm per minute are found to be higher than the value of Weibull modulus for the specimens of the other tests. As a result the performances of the specimens that have been tested at a crosshead speed of 0.1 and 0.5 mm per minute may indicate these speeds are suitable for the compressive test. The differences between the results discussed may be due to the mode of failure that has been discussed in previous paragraph.

A very good correlation coefficient is observed for all the tests. This indicates that the data from the compressive test for the Plaster of Paris correlated well with the Weibull Distribution Equation. In this analysis, the Weibull modulus and characteristic strength of each test may be compared. The Weibull modulus and characteristic strength for the specimens sizes of 18 mm diameter by 15 mm length, 18 mm diameter by 20 mm length and 18 mm diameter by 25 mm length are approximately the same when the test was carried out at crosshead speed 0.1 mm per minute. This is shown in Table 4.3.1.4. It can be seen clearly from Figure 4.3.1.4 that the Weibull curves are close to each other particularly for specimen sizes 18 mm diameter by 15 mm length, 18 mm diameter by 20 mm length and 18 mm diameter by 25 mm length. Such results were obtained when the tests were carried out at crosshead speed 0.1 mm per minute. Table 4.3.1.7 shows the results for the specimens of size 18 mm diameter by 25 mm length that have been tested at various crosshead speeds. It can be seen that the value of Weibull modulus and characteristic strength are approximately the same particularly for the test carried out at crosshead speeds of 1 mm per minute, 0.5 mm per minute and 0.1 mm per minute. These effects are graphically illustrated in Figure 4.3.1.7 for the specimens of size 18 mm diameter by 25 mm length that have been tested at various crosshead speeds. The Weibull curves for crosshead speeds 1, 0.5 and 0.1 mm per minute are close to each other.

As a result, it can be drawn from these tests that a more statistically reliable result can be obtained by carrying out the compressive test for the Plaster of Paris with a crosshead speed of 0.1 mm per minute. The specimen of diameter/length ratio approximately equal to 2:3 is the recommended size of the compressive specimen. With respect to this finding, the 1% failure stress for the compressive strength of Plaster of Paris could be taken as 14 MPa (Table 4.3.1.4 - for specimen size 3). The true strength of Plaster of Paris is 32 MPa, if 99.99 percent failure probability to be taken as a parameter to estimate the true strength of the material. It must be born in mind that these strength parameters may not be universal. It is only applicable to the batches of material which were used at the time of testing.

4.3.2 The Effect of Specimen Size and Crosshead Speed on the Compressive Strength of Opalux

There are two types of test which were designed for the compressive strength testing of Opalux. The first test was to investigate the effect of crosshead speed on the compressive strength of Opalux. Specimens of diameter/length ratio 1/2 were tested under crosshead speeds 0.1, 0.5, 1 and 10 mm per minute. There were two types of specimen sizes used (i.e 2.5 mm diameter by 5 mm length and 3 mm diameter by 6 mm length). The second test was to investigate the effect of specimen diameter/length ratio on the compressive strength of Opalux. This test was carried out at a slow crosshead speed (i.e 0.1 mm per minute). Tables 4.3.2.1 and 4.3.2.2, and Figures 4.3.2.1 and 4.3.2.2 show the results of the first test. The results for the second test are shown in Tables 4.3.2.3, 4.3.2.4 and 4.3.2.5 and Figures 4.3.2.3, 4.3.2.4 and 4.3.2.5 .

Even though the specimens tested in Table 4.3.2.1 and 4.3.2.2 were both of diameter/length ratio of 1:2, One-way analysis of variance showed that there was a highly significant variation between the mean compressive strength of Opalux when the test was carried out at various crosshead speeds, for the specimens of size 2.5 mm diameter by 5mm length ($P<0.01$). However there was no significant variation between the mean compressive strength of Opalux when the test was carried out at various crosshead speeds, for the specimens of size 3mm diameter by 6mm length ($P>0.05$). This shows that the standard diameter/length of 1:2 for the compressive test that has been discussed in Chapter 2 is found to be unreliable. The size of the specimen itself is thought to have some effect on the compressive strength.

Table 4.3.2.1 shows, for 2.5 mm diameter by 5 mm length, that the characteristic and mean strength of Opalux increase as crosshead speeds increase. However there is no difference in mean strength at low crosshead speeds (i.e 0.1 and 0.5 mm per minute). This is shown by the Tukey range test where the mean strengths for the test carried out at crosshead speed 0.5 mm per minute and 0.1 mm per minute are not significantly different from each other ($p>0.05$). This is because the strain rate is very slow, and crack propogation ~~propogatation~~ from a flaw in the specimen is also slow. When the crack reaches the most critical flaw size, a failure occurs. A mode of failure may not be due to the local elastic and plastic deformation as the mean strengths of the specimens tested at a crosshead speeds of 0.1 and 0.5 mm per minute are less than the mean strengths of the specimens tested at other crosshead speeds. Catastrophic failure is suspected to have occurred. ~~occured~~. This is evidently shown by a poor correlation coefficient as the catastrophic failure may produced a scatter results. The reason for this is because of the degree of polymerisation. The degree of polymerisation in the specimens of size 2.5 mm diameter by 5 mm length may be completed. This will result in a higher crosslink density of the polymer (Braden and Causton:1973, Braden, Causton and Clarke:1976) and it may lower the water absorption. The strength of a material increases as the crosslink density increases. The same conclusion was reached when the results were analysed by Weibull statistic. Figure 4.3.2.1 shows a plot of Weibull curves for the specimens of 2.5 mm diameter by 5 mm length that had been tested at various crosshead speeds. The curve for the tests carried out at a crosshead speed of 0.5 and 0.1 mm per minute are very close to each other. It can be seen from Table 4.3.2.1 that the value of Weibull modulus and characteristic strength for the test at a crosshead speeds of 0.5 and 0.1 mm per minute are approximately the same. The Weibull curves for the specimens that were tested at a crosshead speed of 1 and 10 mm per minute are separated from each other, showing the difference in compressive strength.

Table 4.3.2.2 shows the results for the compressive strength tests of Opalux for a specimen size 3 mm diameter by 6 mm length. The mean compressive strength of the specimens that have been tested at a crosshead speed of 0.5 mm per minute is less than the mean compressive strength of the specimens that have been tested at the other crosshead speeds. However the Tukey range test shows the mean strengths for each crosshead speed are not significantly different from each other ($p>0.05$). The same conclusion is reached when the results are analysed by Weibull analysis. Figure 4.3.2.2 shows a plot of the Weibull curves for the specimens of 3 mm diameter by 6 mm length that were tested at various crosshead speeds. All the curves are very close to each other except for the test carried out at a crosshead speed of 0.5 mm per minute. It can be seen from Table 4.3.2.2 that the values of Weibull modulus for all the tests are approximately the same but the value of the characteristic strength of the test carried out at a crosshead speed of 0.5 mm per minute makes it a curve detached. In addition the results of the specimens that have been tested at a crosshead speeds of 0.5 and 1 mm per minute may not be reliable as the correlation coefficients are poor when compared to the correlation coefficients of the other tests. This is supported by a high value of standard error of modulus. Therefore the value of Weibull moduli of these test may be doubtful and the tests carried out at a crosshead speed of 0.5 and 1 mm per minute may not be reliable for the compressive test. It can be seen from this experiment that a crosshead speed of 0.1 mm per minute may produce a more reliable result than the test carried out at a crosshead speed of 10 mm per minute when a specimen size 3 mm diameter by 6 mm length is used for the compressive test. This is because the specimens that have been tested at a crosshead speed of 0.1 mm per minute give a higher Weibull modulus. The performance the specimens that have been tested at a crosshead speed of 0.1 mm per minute is also better than the performance of the specimens that have been tested at a crosshead speed of 10 mm per minute. The value of Weibull modulus at a low crosshead speed (0.1 mm per minute) is the same (equal to 15), however it can be seen from Table 4.3.2.1 and 4.3.2.2 that the mean and characteristic strengths decrease as specimen size increases. The characteristic and mean strength of the 2.5 mm diameter specimens are higher than 3 mm diameter specimens. Table 4.3.2.1 shows that the characteristic strengths for crosshead speeds 0.1 and 0.5 mm per minute (284 MPa) are higher than for a crosshead speed of 0.1 mm per minute (240 MPa) from Table 4.3.2.2. This is because of the effect of the degree of polymerisation on the strength of polymeric materials, as has been discussed previously.

The previous discussion has shown the effect of specimen size on the compressive strength of Opalux. It also showed that there was no variation between the mean compressive strength of Opalux when the specimen sizes 2.5 mm diameter by 5 mm length and 3 mm diameter by 6 mm length were tested at a crosshead speed of 0.1 mm per minute. Further specimen sizes were studied to investigate the effect of specimen size at slow crosshead speed. The results of the test for specimens 4 mm, 5 mm and 6 mm length with various diameters are shown in Tables 4.3.2.3, 4.3.2.4 and 4.3.2.5 and Figures 4.3.2.3, 4.3.2.4 and 4.3.2.5.A crosshead speed of 0.1 mm per minute was used for these tests.

One-way analysis of variance shows there is a significant difference ($P<0.001$) between the mean compressive strengths of Opalux for various diameters of the specimen for a specimen length of 4 mm (Table 4.3.2.3). But the Tukey range test shows there is no significant difference between the mean compressive strength of Opalux for specimen 4 mm diameter and 6 mm diameter ($p>0.05$). This effect can also be seen in Figure 4.3.2.3, where the Weibull curves for the specimens of 4 mm and 6 mm diameter are close to each other. The mode of failure for the specimens of size 4 mm diameter by 4 mm length and 6 mm diameter by 4 mm length is due to the complex stress developed in the specimens of diameter/length ratio of greater than 1:2 (Robert:1885). That may be the reason why the compressive strength of the specimens of size 4 mm diameter by 4 mm length and 6 mm diameter by 4 mm length are the same. The other reason may be due to the size and number of flaws in the specimens. The probability of more flaws being present in a large specimen is greater than the probability of more flaws may being present in a small specimens. The strength decreases as the number and or sizes of flaws increases. The strength may be further lowered when the degree of polymerisation decreases (Ruyther and Oysead:1982, Asmussen:1982, Ruyther and Svendsen:1978). The compressive strength of the specimens of size 2 mm diameter by 4 mm length is higher when compared to the compressive strength of the other specimen sizes. This is may be due to the high degree of polymerisation and less flaws being present in the specimens. These effects are also found for the results of the compressive strength of Opalux for various diameter of the specimen for the specimens of length of 5 mm (Table 4.3.2.4).Table 4.3.2.4 shows that the value of the characteristic the mean compressive strength for the specimens of 4 mm and 6 mm diameter are approximately the same.

From the results above, it is suggested that the specimen of size 4 mm diameter by 4 mm length and 6 mm diameter by 4 mm length (Table 4.3.2.3) and 4 mm diameter by 5 mm length and 6 mm diameter by 5 mm length (Table 4.3.2.4) are not suitable for the compressive strength test of Opalux. This is may due to the complex stresses developed in the specimen before fracture (Robert:1985). In addition all the specimen sizes tested for the above tests are of diameter/length ratios greater than 1. Specimens of diameter/length ratio of 1:2 are said to give more reliable results (Robert:1985). It is shown here that for the specimens of diameter/length ratio of 1:2 (i.e for specimen sizes 2 mm diameter by 4 mm length and 2.5 mm diameter by 5 mm length) a higher compressive strength is obtained when compared to the compressive strength of the other specimen sizes. This has been illustrated clearly by the Weibull statistic where the performances of these specimen sizes are better than the performances of the other specimen sizes. The reliability of the specimens of diameter/length ratio approximately equal to 1:2 are again demonstrated in the Table 4.3.2.5.

One-way analysis of variance shows there is no significant difference ($P = 0.33$) between the mean compressive strength of Opalux for the various diameters of the specimen for the specimens of length of 6 mm (Table 4.3.2.5). A Tukey range test also shows there is no significant difference between the mean compressive strength of Opalux for each group ($p>0.05$). It can be seen from Table 4.3.2.5 that there is no significant difference between the mean strength for specimen 3 mm and 4 mm diameter (T-Test, $P = 0.85$). This may be because the diameter/length ratio of these specimens is approximately, (or equal), to 1:2. This agrees well with the theory discussed in chapter two. The mean compressive strength of Opalux for the 5 mm diameter specimens is found to be higher than 3 mm diameter and 4 mm diameter result but the correlation coefficient for the specimen of 5 mm diameter is low when compared to the other groups. This may be due to the complex stress system developed in the specimen before fracture (Robert:1985). This effect is shown graphically in Figure 4.3.2.5. The curve for diameters 3 mm and 4 mm share the same curve. The Weibull curve for the 5 mm specimen is isolated from others of the group although it has approximately the value of Weibull modulus. This is mainly because it has a higher characteristic strength.

Based on the results of this investigation, particular attention should be focused on Table 4.3.2.5 and Figure 4.3.2.5. This is because at a low crosshead speed of 0.1 mm per minute, reliable results are obtained for the compressive test when a specimen size of 3 mm diameter by 6 mm length or 4 mm diameter by 6 mm length is used.

4.3.3 The Effect of Specimen Size and Crosshead Speed on The Compressive Strength of Occlusin

The effect of specimen size (i.e Diameter/Length ratio) on compressive strength and the effect of the crosshead speed on compressive strength of Occlusin were investigated. A series of compressive tests had been carried out for specimens of diameter 4 mm, 5 mm and 6 mm. The length of the specimens was 6 mm. The specimens had been stored in distilled water for 7 days at 37 ^{o}C prior to testing.

Crosshead speeds of 0.1, 0.5, 1 and 10 mm per minute were used for each specimen size. The results for the effect of the crosshead speed on compressive strength are shown in Tables 4.3.3.1, 4.3.3.2, and 4.3.3.3 and Figures 4.3.3.1, 4.3.3.2, and 4.3.3.3 . Tables 4.3.3.4, 4.3.3.5, 4.3.3.6, and 4.3.3.7 and Figures 4.3.3.4, 4.3.3.5, 4.3.3.6, and 4.3.3.7 show the results for the effect on compressive strength of specimen size.

Analysis of variance (ANOVA) shows that there was a very highly significant difference between the mean compressive strength for the various crosshead speeds ($P<0.001$). There was also a very highly significant difference between the mean compressive strength for varying specimen size ($P<0.001$). This indicates that the compressive strength of Occlusin is affected by crosshead speed and specimen size.

The effect of crosshead speed on the compressive strength of Occlusin analysed by One-way analysis of variance, showed that there was a significant difference between strengths for varing crosshead speed if the specimen size of 6 mm diameter by 6 mm length was used (Table 4.3.3.3). The Tukey range test showed that the mean compressive strength for the tests carried out at crosshead speeds 10 mm per minute and 1 mm per minute were not significantly different from each other (T-Test, $P = 0.383$) at the 0.05 significance level. The diameter\length ratio of the specimens tested in this test is 1:1. The size of flaws and the number of flaws in the specimens and the degree of polymerisation may not be significant because the specimens of the same size are used. It is assumed that the flaw size, the number of flaws and the degree of polymerisation are the same for all the specimens. Therefore failures may be due to the complex stress developed during testing (Robert:1985). That is why the mean compressive strength of the specimens tested at crosshead speeds of 10 and 1 mm per minute are approximately the same. This is shown graphically by the Weibull statistic in Figure 4.3.3.3. The Weibull curves for the tests carried out at crosshead speeds 10 mm per minute and 1 mm per minute are close to each other. This is because the Weibull modulus and characteristic strength of these groups are approximately the same. The performance of these groups are therefore about the same. However the performance at a lower probability level of failure of the specimen group that has been tested at a crosshead speed 0.1 mm per minute was better than the other groups. However, according to the Normal statistic, the performance of the specimen group that has been tested at a crosshead speed 0.5 mm per minute was better than other groups. The major feature for the high value of stress predicted at 0.01 percent failure probability for the specimen group that has been tested at 0.5 mm per minute was the high mean strength. This is not the case for the Weibull statistic. The characteristic strength of the specimen group that has been tested at a crosshead speed 0.1 mm per minute was the lowest, yet it has a better performance when compared to the other groups. This however may be because of it's high Weibull modulus. Thus according to these results, a crosshead speed of 0.1 mm per minute may be the most suitable for the compressive test.

There is a significant difference between the mean compressive strength with varying crosshead speed (Oneway,P<0.001) when the specimen size is 4 mm diameter by 6 mm length (Table 4.3.3.1). However the Tukey range test shows that there is no significant difference between the mean compressive strength for the test carried out at a crosshead speeds of 0.5, 1 and 10 mm per minute for a specimen size 4 mm diameter by 6 mm length (Table 4.3.3.1). In addition the mean compressive strengths of the tests carried out at a crosshead speeds of 0.1 and 0.5 mm per minute are not significantly different (T-Test, P=0.854). This is clearly shown in Figure 4.3.3.1 that the Weibull curves for the tests carried out at a crosshead speeds of 0.5, 1 and 10 mm per minute are randomly plotted. This shows that the compressive ~~compresive~~ strengths of the specimens tested at these crosshead speeds are different. However at an approximately 63 percent failure probability, which represents the characteristic strength, the value of the strengths for the specimens tested at a crosshead speeds of 0.5, 1 and 10 mm per minute are the same, as is shown by the intersection of the curves. The Weibull curve for the test carried out at a crosshead speed of 0.1 mm per minute is well separated from the other curves. The compressive strength of the specimens for the test carried out at a crosshead speed of 0.1 mm per minute is less than the compressive strength of the specimens for other tests. It is assumed that the flaw size, the number of flaws and the degree of polymerisation are the same. Therefore the size of flaws and the number of flaws in the specimens and the degree of polymerisation may have the same effect on the compressive strength of Occlusin. In addition, the effect of complex stress may also not be significant as the diameter/length ratio of the specimens is approximately 1:2. The only significant reason may be due to the crosshead speed of the test. It is sensible to say that at failure, a local elastic and plastic deformation may be developed in the specimens. This behaviour may be responsible for lowering the compressive strength of Occlusin.

Weibull statistic shows that the correlation coefficients for the test carried out at 0.1 and 0.5 mm per minute are lower than the correlation coefficients for the test carried out at 10 and 1 mm per minute. This shows that the results of the test being carried out at a slow crosshead speed are a more reliable fit to the Weibull distribution. In addition the performance of the specimen groups for the tests carried out at crosshead speeds 0.5 mm per minute and 0.1 mm per minute were better than for the other groups.

For the specimen size 5 mm diameter by 6 mm length, Figure 4.3.3.2 shows the Weibull curves for all the tests are separated from each other. This indicates the compressive strength of the specimens tested at all crosshead speeds are different from each other. The compressive strength of the specimens increases as the crosshead speed increases. This variation in the compressive strength may be because of the effect of crosshead speed. It is assumed that the flaw size, the number of flaws and the degree of polymerisation are the same as for all specimen. Therefore the size of flaws and the number of flaws in the specimens and the degree of polymerisation may have the same effect on the compressive strength of Occlusin. In addition, complex stress may be developed at failure but since all the tests used the same specimen size, the effect of complex stress will be the same for all the specimens. This complex stress however increased the compressive strength of the specimen of 5 mm diameter by 6 mm depth. As the mean strength of the specimen size 5 mm diameter by 6 mm length (Table 4.3.3.2) is higher when compared to the mean strength of the specimen size 4 mm diameter by 6 mm length (Table 4.3.3.1). A local elastic and plastic deformation may be developed at failure (Darvell:1990) and this may be more significant when the test is carried out at a low crosshead speed. That may be the reason why the compressive strength of the specimen size 5 mm diameter by 6 mm length decreases as the crosshead speed decreases.

One-way analysis shows that at a high crosshead speed, 10 mm per minute, there is a highly significant difference between strengths for different specimen sizes (Table 4.3.3.4). This is shown by Figure 4.,3.3.4 where the Weibull curves are scattered. The variation of compressive strength of the specimens tested at a crosshead speed of 10 mm per minute may be due to the difference in specimen size. This clearly indicates the effect of specimen size on the compressive strength of Occlusin. These results also show that a crosshead speed of 10 mm per minute is not suitable for compressive test. The effect of specimen size on the compressive strength may be due to the porosities or flaws. Photo-activated composite resin may contain porosities (Reinhardt et al:1982, Gotfredsen et al:1983). Possible adverse effects of porosity are increased water sorption and decreased degree of conversion due to the inhibition from entrapped air (Dijken, Ruyther and Holland:1986). This may be the reason why some of the dimethacrylate molecules remain unreacted in the composite resin and this may cause a low crosslink density (Ruyther and Svendsen:1978, Ruyther and Oysead:1982, Asmussen:1982). The above factors may lower the strengths of a photo-activated composite resin (Ruyther and Svendsen:1978, Ruyther and Oysead:1982, Asmussen:1982). That may explain why the strength of the specimen size 6 mm diameter by 6 mm length is lower than the strength of the specimen size 5 mm diameter by 6 mm length. However the strength of the specimen sizes 5 mm diameter by 6 mm length and 6 mm diameter by 6 mm length is higher than the compressive strength of the specimen size 4 mm diameter by 6 mm length. This may be due to the behaviour at failure. This has been discussed previously, a complex stress may be developed at failure for the diameter/length ratio of the specimen is greater than 1:2 or perhaps approximately equal to 1:1. This behaviour significantly increased the compressive strength of Occlusin. This is the reason why the compressive strength of the specimen size 4 mm diameter by 6 mm length is low. Table 4.3.3.4 shows the Weibull Modulus, characteristic strength and mean strength for the specimen size 5 mm diameter by 6 mm length are the highest among the group. The performance of this specimen is also better than the performances of the other specimen sizes.

For the tests carried out at a crosshead speed 1 mm per minute, one-way analysis of variance shows that there is no significant difference (P=0.01) between strengths for varying specimen size. The Tukey range test also shows that the mean compressive strength of all the specimen sizes are not significantly different from each other at the 0.05 significant level. However Weibull statistic shows that the correlation coefficient for the test carried out at this crosshead speed is not very satisfactory. Only the specimen size 5 mm diameter by 6 mm length shows a good fit to the Weibull distribution. In addition, the performance at a lower probability of failure of the specimen size 5 mm diameter by 6 mm length is better than the other specimen sizes as the estimated stress at 0.01 percent failure probability is higher than other specimen sizes. Figure 4.3.3.5 shows the Weibull curves are randomly plotted. However it can be concluded from the Figure that the compressive strengths of the specimen sizes 5 mm diameter by 6 mm length and 6 mm diameter by 6 mm length are approximately the same and the compressive strength of the specimen size 4 mm diameter by 6 mm length is different from the compressive strengths of the other specimen sizes. It can be seen also that the strength of the specimen size 4 mm diameter by 6 mm length is lower than the strength of the other specimen sizes. These variations have been discussed in the previous paragraph. Thus a crosshead speed of 1 mm per minute may be not suitable for the compressive test. However it is shown from the results of the test carried out at a crosshead speed of 1 mm per minute that it fit the Weibull distribution better that other specimen sizes. This is shown by a high value of correlation coefficient.

Table 4.3.3.6 shows the results for the tests carried out at crosshead speed 0.5 mm per minute. There is a highly significant difference between the mean compressive strength for varying specimen size ($p<0.05$). The mean strength increases as specimen size increases. However the mean strengths of the specimen size 4 mm diameter by 6 mm diameter and 5 mm diameter by 6 mm diameter are approximately the same. This is shown in Figure 4.3.3.6 where the Weibull curves for the specimen sizes 4 mm diameter by 6 mm diameter and 5 mm diameter by 6 mm diameter are close to each other. This may be due to the different specimen size. As previously discussed, the effect of specimen size on the compressive strength may be due to the porosities or flaws. This may be also due to the behaviour at failure. This has been discussed previously that a complex stress may be developed at failure for the diameter/length ratio of the specimen is greater than 1:2 or perhaps approximately equal to 1:1. However this behaviour is found to be less significant when a low crosshead speed is used in the testing as plastic deformation may developed. This is shown by the compressive strength of the specimen size 5 mm diameter by 6 mm length. At a higher crosshead speed, the compressive strength of the specimen sizes 5 mm diameter by 6 mm length and 6 mm diameter by 6 mm length are approximately the same (Table 4.3.3.4 and Table 4.3.3.5). However at a lower crosshead speed, the compressive strength of the specimen sizes 4 mm diameter by 6 mm length and 5 mm diameter by 6 mm length are approximately the same (Table 4.3.3.6 and Table 4.3.3.7). The compressive strength of specimen size 6 mm diameter by 6 mm length is found to be higher when compared to the compressive strength of the other specimen sizes. This shows the complex stress behaviour at failure is still significant for the specimen size 6 mm diameter by 6 mm length even though a slow crosshead speed in used. However Weibull statistic shows that the value of Weibull modulus is low. The results of this test may be unreliable and this has been shown by a poor performance even though it has a higher value of mean strength. In addition the correlation coefficient of the test for specimen size 6 mm diameter by 6 mm length is poor when compared the test of other specimen sizes. The performance of the specimen size 4 mm diameter by 6 mm length at a lower failure probability (0.01 percent failure probability), is better than other specimen sizes. Even though the characteristic strength of the specimens of size 6 mm diameter by 6 mm length is higher than for the specimens of size 4 mm diameter by 6 mm length. With respect to these results, the specimen size of 4 mm diameter by 6 mm length may given reliable results when a crosshead speed of 0.5 mm per minute is used for the compressive test.

Table 4.3.3.7 shows the results of the compressive tests that have been carried out at crosshead speed 0.1 mm per minute. There is a highly significant difference between the mean strength for varying specimen size ($p<0.001$). The Tukey range test shows that the mean strength of the tests for the specimen sizes 5 mm diameter by 6 mm length and 6 mm diameter by 6 mm length are not significantly different at the 0.05 significant level. The mean strength of the specimen sizes 5 mm diameter by 6 mm length and 6 mm diameter by 6 mm length is higher than the mean strength of the specimens of size 4 mm diameter by 6 mm length. However the estimated stress at 0.01 percent failure probability for the specimen size 5 mm diameter by 6 mm length and 6 mm diameter by 6 mm length are less than for the specimen size 4 mm diameter by 6 mm length. Thus the performance of the specimen size 4 mm diameter by 6 mm length at a lower probability of failure is better that the performance of the specimen size 5 mm diameter by 6 mm length and 6 mm diameter by 6 mm length. As before the effect of specimen size on the compressive strength may be due to the porosities or flaws and the behaviour at failure. This has been discussed previously, i.e a complex stress may be developed at failure when the diameter/length ratio of the specimen is greater than 1:2 or perhaps approximately equal to 1:1. However this behaviour is found to be less significant when a low crosshead speed is used in the testing as plastic deformation may develop. That is why the mean compressive strength of the specimens of size 6 mm diameter by 6 mm length that have been tested at a crosshead speed of 0.1 mm per minute is less than the mean compressive strength of the specimens of the same specimen size when tested at a crosshead speed of 0.5 mm per minute (Table 4.3.3.6). Weibull statistic for the tests described above also give the same agreement. Weibull modulus decreases as specimen size increases. Although the characteristic strength of the specimen size 5 mm diameter by 6 mm length and 6 mm diameter by 6 mm length are greater than the characteristic strength of the specimen size 4 mm diameter by 6 mm length but the estimated stress at 0.01 percent failure probability of the specimen size 4 mm diameter by 6 mm length is greater than for the other specimen sizes. Thus the performance of the specimen size 4 mm diameter by 6 mm length at a lower probability of failure is better than the performance for the other specimen sizes. The specimen size of 4 mm diameter by 6 mm would be used for the compressive test. Specimen size 4 mm diameter by 6 mm length gave more reliable results when a crosshead speed of 0.1 mm per minute was used. The other specimen sizes may not suitable because the results of these tests were not reliable and this was shown by a low value of correlation coefficient and a poor performances of the tests.

4.4 Summary and Conclusion

The results of the investigation show, specimen size and crosshead speed affect the compressive strength. It is found that the crosshead speed of 0.1 mm per minute is suitable for use in the compressive test when a specimen of diameter/length ratio of approximately equal to 1:2 is used. Specimen size of 4 mm diameter by 6 mm length is found the most reliable specimen size for the compressive test of Composite resin at a crosshead speed of 0.1 mm per minute.. For the compressive test of plaster of paris, a specimen size 18 mm diameter by 25 mm length has given the most reliable results with the crosshead speed of 0.1 mm per minute. For the specimen size of diameter by length ratio of approximately equal to 1:1, a crosshead speed of 1 mm per minute may be found suitable. Therefore the conclusion that can be drawn from this study is that the specimen size 4 mm diameter by 6 mm length may give reliable results when a crosshead speed of 0.1 mm per minute is used for the compressive test.

CHAPTER FIVE

DIAMETRAL TENSILE TEST

5.1 The Determination Of The Optimum Specimen Size And Crosshead Speed For The Diametral Tensile Test.

This part of the investigation was conducted to evaluate the effect of test parameters on the diametral tensile strength of some brittle dental restorative materials. Such as:-

(a) the effect of crosshead speed on the diametral tensile test.

(b) the effect of specimen size on the diametral tensile test.

These investigations were conducted firstly, to study the effect of crosshead speed on the diametral tensile strength of the brittle dental materials. The optimum crosshead speed for the diametral tensile test would be determined. It would be used in further investigations to determine the strength parameters of the dental restorative materials. Crosshead speeds of 0.1, 0.5, 1 and 10 mm per minute were studied in this investigation. Secondly, the effect of the specimen size on the diametral tensile strength of the brittle dental materials was investigated. The most suitable specimen size would be determined and would be used in further investigations to determine the strength parameter of the dental restorative materials. It has been said in chapter two that the optimun specimen diameter/length ratio for the diametral tensile test was 1:1. In this investigation various specimen sizes of diameter/length ratio of 1:1 have been tested. The specimens of other diameter/length ratios are also studied. The materials used for the diametral tensile tests were Occlusin, Opalux and plaster of paris.

5.2 Methods

5.2.1 Plaster of Paris

For the diametral tensile test, specimens of four different diameter-length ratios were prepared. The specimens were obtained from a mould of constant 18 mm diameter. The lengths of the specimens were 10 mm, 15 mm, 20 mm, and 25 mm. Four crosshead speeds were selected. They ranged from the slowest speed of 0.1 mm per minute to the fastest speed of 10 mm per minute. Two intermediate rates were 0.5 mm per minute and 1 mm per minute were used. For each size of specimen, a total of 120 specimens were prepared i.e 30 specimen for every ~~cross head~~ Crosshead speed, hence a grand total of 480 specimens were tested.

The specimens were prepared in accordance to the procedure described in chapter three (section 3.2). All the tests were carried out by using the Instron Universal testing machine (Model 1195) shown in Photograph J. The data was analysed by the computer program as described in chapter four.

5.2.2 Opalux

For the diametral tensile test of Opalux, a group of specimens of four different sizes were prepared. They were 3 mm diameter by 2 mm length, 4 mm diameter by 3 mm length, 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length. These gave different diameter/length ratios i.e 3:2 and 4:3 for the first two sizes and 1:1 for the last two. Crosshead speeds of 0.1 mm per minute, 0.5 mm per minute, 1 mm per minute and 10 mm per minute were used for each specimen size. Thirty specimens were prepared for each crosshead speed. Hence a total of 480 specimens were tested. The specimens were stored in distilled water prior to testing.

The specimens were prepared in accordance to the procedure described in chapter three (section 3.3). All the tests were carried out by using the Instron Universal testing machine (Model 1195) that is shown in Photograph J. The data was analysed by the computer program as described in chapter four.

5.2.3 Occlusin

For the diametral tensile test of Occlusin, a group of specimens of four different sizes were prepared. They were 3 mm diameter by 2 mm length, 3 mm diameter by 3 mm length, 4

5.3 Results and Discussions

Data from the mechanical test for each type of material was analysed by the 'Strength Analysis'. As previously mentioned this was done by the computer. The output of the program such as Weibull modulus, standard error of modulus, characteristic strength and stress at various levels of failure probability were recorded. A typical set of data and the print out of the Weibull analysis is shown in the appendix B.

Mean strength, percentage of deviation coefficient and stress at various levels of failure probability from Normal distribution was also calculated. Stresses at various levels of probability from the Weibull distribution and the Normal distribution were compared.

The results of all the mechanical tests for all types of material under investigation are put in the form of Tables for the analysis of the Weibull distribution and Normal distribution. A graphical representation of the results by the Weibull distribution is shown in the Figures.

TABLE 5.3.1.1

Summary of Weibull analysis-Diametral tensile strength of Plaster of various specimen sizes* which is tested at crosshead speed of 10mm/min.

Specimen Size	1	2	3	4
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	5.2 3.2 0.14 0.98	6.9 3.3 0.23 0.97	8.8 3.1 0.26 0.97	4.8 3.1 0.14 0.97
Mean Strength+ Deviation Coefficient (%)	2.9 19.6	3.1 15.5	2.9 12.5	2.9 21.8
Stress+ at Failure Probability				
0.01% - Weibull Normal	0.5 2.52	0.9 2.78	1.1 2.66	0.5 2.78
1% - Weibull Normal	1.3 2.66	1.7 2.9	1.8 2.75	1.2 2.83
99.99% - Weibull Normal	4.2 3.28	4.2 3.42	3.7 3.14	4.3 3.01

* Size 1 = 18mm diameter by 10mm length, size 2 = 18mm diameter by 15mm length, size 3 = 18mm diameter by 20mm length and size 4 = 18mm diameter by 25mm length.
+ unit in Mpa.
Oneway analysis of variance-No significant difference between compressive strength and Specimen size (P>0.05).

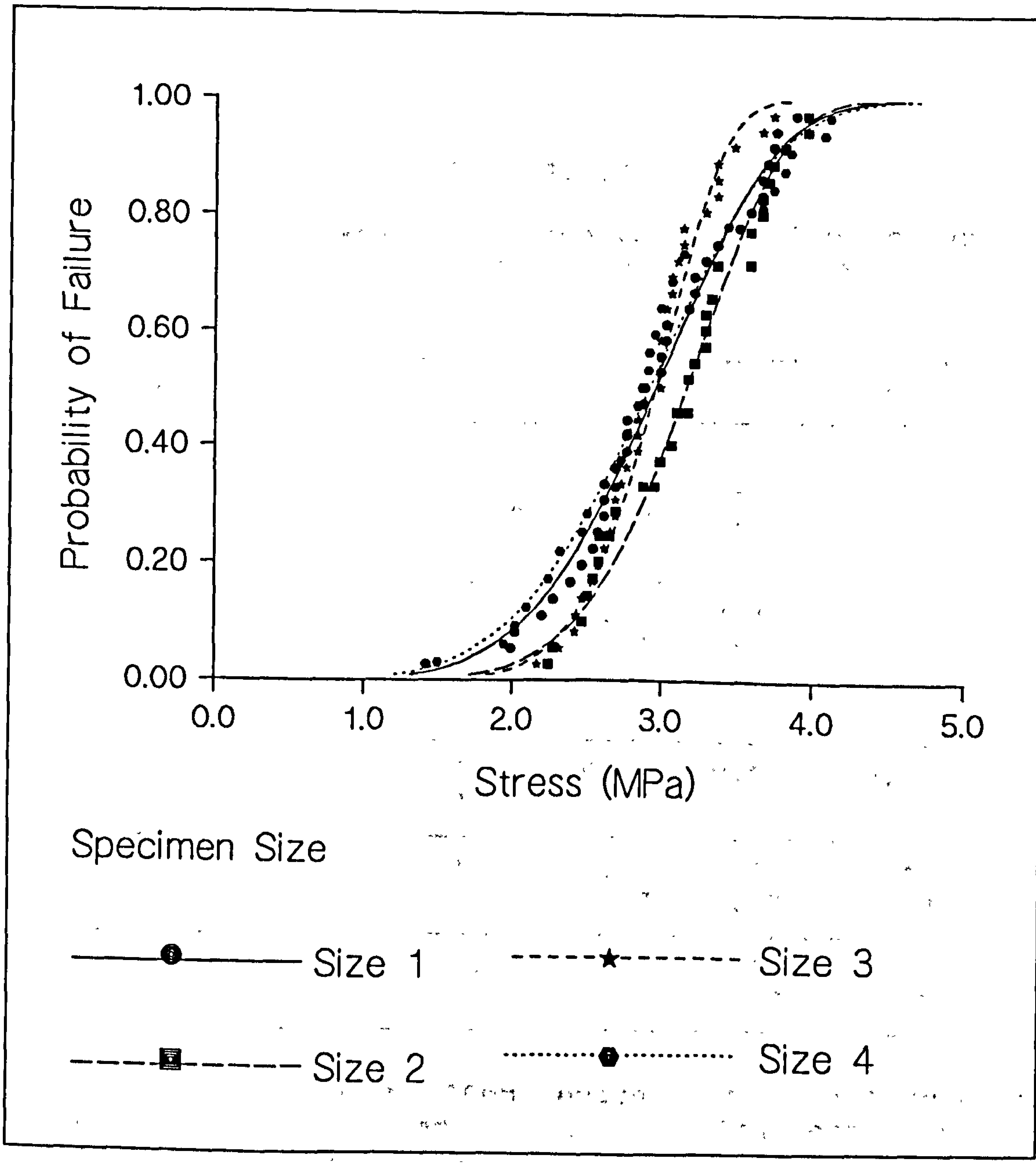


FIGURE 5.3.1.1

Diametral tensile strength of Plaster- Probability of failure versus diametral tensile stress of various specimen sizes at Crosshead Speed 10mm/min.

Size 1 = 18mm diameter by 10mm length, size 2 = 18mm diameter by 15mm length,
size 3 = 18mm diameter by 20mm length and size 4 = 18mm diameter by 25mm length.

TABLE 5.3.1.2

Summary of Weibull analysis-Diametral tensile strength of Plaster of various specimen sizes* which are tested at crosshead speed of 1mm/min.

Specimen Size	1	2	3	4
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	4.7 3.3 0.09 0.99	6.2 3.3 0.18 0.97	6.6 3.6 0.18 0.98	4.6 3.7 0.10 0.99
Mean Strength+ Deviation Coefficient (%)	3.0 22.0	3.1 17.1	3.4 16.0	3.4 22.2
Stress+ at Failure Probability				
0.01% - Weibull Normal	0.5 2.55	0.8 2.74	0.9 3.03	0.5 2.89
1% - Weibull Normal	1.2 2.72	1.6 2.87	1.6 3.17	1.4 3.08
99.99% - Weibull Normal	4.6 3.45	4.3 3.46	4.6 3.77	5.2 3.91

* Size 1 = 18mm diameter by 10mm length, size 2 = 18mm diameter by 15mm length, size 3 = 18mm diameter by 20mm length and size 4 = 18mm diameter by 25mm length.
+ unit in Mpa
Oneway analysis of variance-Significant difference between compressive strength and Specimen size (P<0.05).

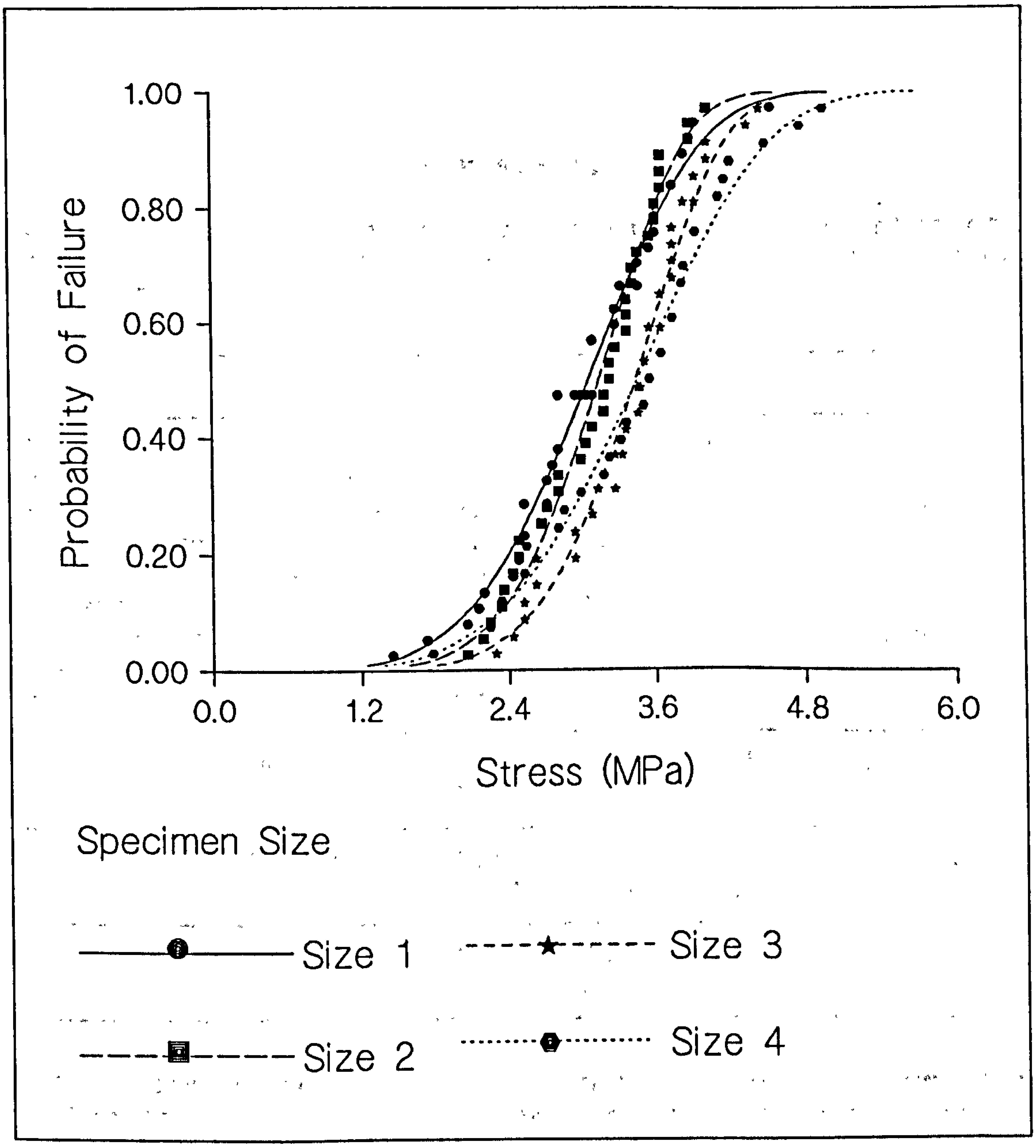


FIGURE 5.3.1.2

Diametral tensile strength of Plaster- Probability of failure versus diametral tensile stress of various specimen sizes at Crosshead Speed 1 mm/min.

Size 1 = 18mm diameter by 10mm length, size 2 = 18mm diameter by 15mm length, size 3 = 18mm diameter by 20mm length and size 4 = 18mm diameter by 25mm length.

TABLE 5.3.1.3

Summary of Weibull analysis-Diametral tensile strength of Plaster of various specimen sizes* which are tested at crosshead speed of 0.5mm/min.

Specimen Size	1	2	3	4
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	4.0 3.4 0.13 0.97	6.1 3.5 0.16 0.98	6.4 3.5 0.34 0.92	4.1 3.5 0.09 0.99
Mean Strength+ Deviation Coefficient (%)	3.0 24.9	3.2 17.7	3.2 17.4	3.2 24.9
Stress+ at Failure Probability				
0.01% - Weibull Normal	0.3 2.5	0.8 2.83	0.8 2.82	0.4 2.66
1% - Weibull Normal	1.1 2.68	1.6 2.96	1.7 2.96	1.1 2.86
99.99% - Weibull Normal	4.9 3.5	4.4 3.58	4.4 3.58	5.1 3.74

* Size 1 = 18mm diameter by 10mm length, size 2 = 18mm diameter by 15mm length, size 3 = 18mm diameter by 20mm length and size 4 = 18mm diameter by 25mm length.
+ unit in Mpa.
Oneway analysis of variance-Very highly no significant difference between compressive strength and Specimen size (P>0.5).

TABLE 5.3.1.3

Summary of Weibull analysis-Diametral tensile strength of Plaster of various specimen sizes* which are tested at crosshead speed of 0.5mm/min.

Specimen Size	1	2	3	4
Weibull Modulus	4.0	6.1	6.4	4.1
Characteristic Strength+	3.4	3.5	3.5	3.5
Standard Error of Modulus	0.13	0.16	0.34	0.09
Coeff. of Correlation	0.97	0.98	0.92	0.99
Mean Strength+	3.0	3.2	3.2	3.2
Deviation Coefficient (%)	24.9	17.7	17.4	24.9
Stress+ at Failure Probability				
0.01% - Weibull	0.3	0.8	0.8	0.4
Normal	2.5	2.83	2.82	2.66
1% - Weibull	1.1	1.6	1.7	1.1
Normal	2.68	2.96	2.96	2.86
99.99% - Weibull	4.9	4.4	4.4	5.1
Normal	3.5	3.58	3.58	3.74

* Size 1 = 18mm diameter by 10mm length, size 2 = 18mm diameter by 15mm length, size 3 = 18mm diameter by 20mm length and size 4 = 18mm diameter by 25mm length.
+ unit in Mpa.
Oneway analysis of variance-Very highly no significant difference between compressive strength and Specimen size (P>0.5).

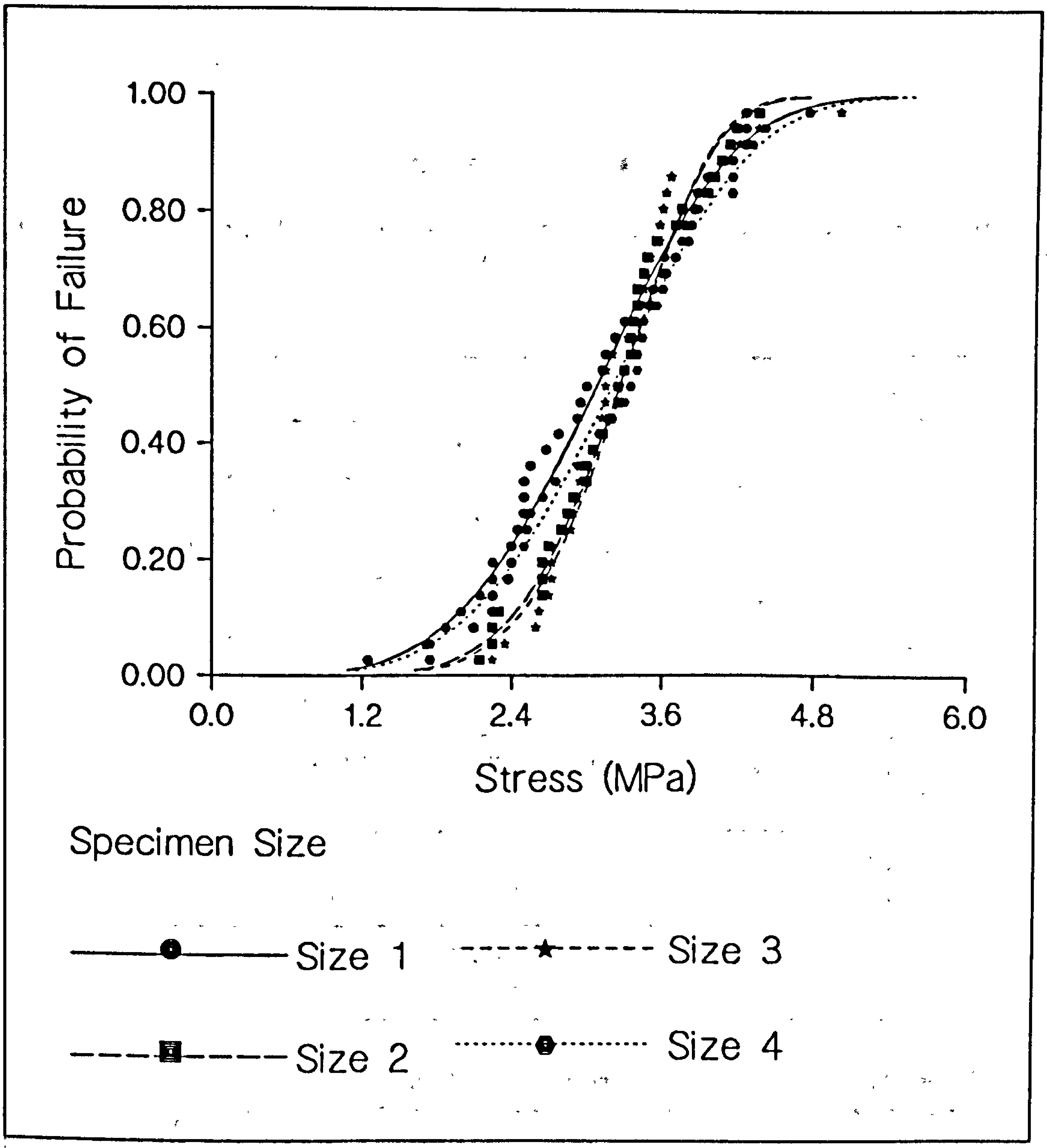


FIGURE 5.3.1.3

Diametral tensile strength of Plaster- Probability of failure versus diametral tensile stress of various specimen sizes at Crosshead Speed 0.5mm/min.

Size 1 = 18mm diameter by 10mm length, size 2 = 18mm diameter by 15mm length, size 3 = 18mm diameter by 20mm length and size 4 = 18mm diameter by 25mm length.

TABLE 5.3.1.4

Summary of Weibull analysis-Diametral tensile strength of Plaster of various specimen sizes* which are tested at crosshead speed of 0.1mm/min.

Specimen Size	1	2	3	4
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	4.3 3.9 0.12 0.97	5.2 3.6 0.13 0.98	4.2 3.6 0.16 0.95	5.9 4.0 0.20 0.96
Mean Strength+ Deviation Coefficient (%)	3.5 24.9	3.3 20.9	3.3 26.2	3.7 18.0
Stress+ at Failure Probability				
0.01% - Weibull Normal	0.5 2.91	0.6 2.83	0.4 2.72	0.8 3.25
1% - Weibull Normal	1.3 3.13	1.5 3.01	1.2 2.93	1.2 3.42
99.99% - Weibull Normal	5.5 4.09	4.8 3.77	5.2 3.88	5.1 4.15

* Size 1 = 18mm diameter by 10mm length, size 2 = 18mm diameter by 15mm length, size 3 = 18mm diameter by 20mm length and size 4 = 18mm diameter by 25mm length.
+ unit in Mpa.
Oneway analysis of variance-Significant difference between compressive strength and Specimen size (P>0.05).

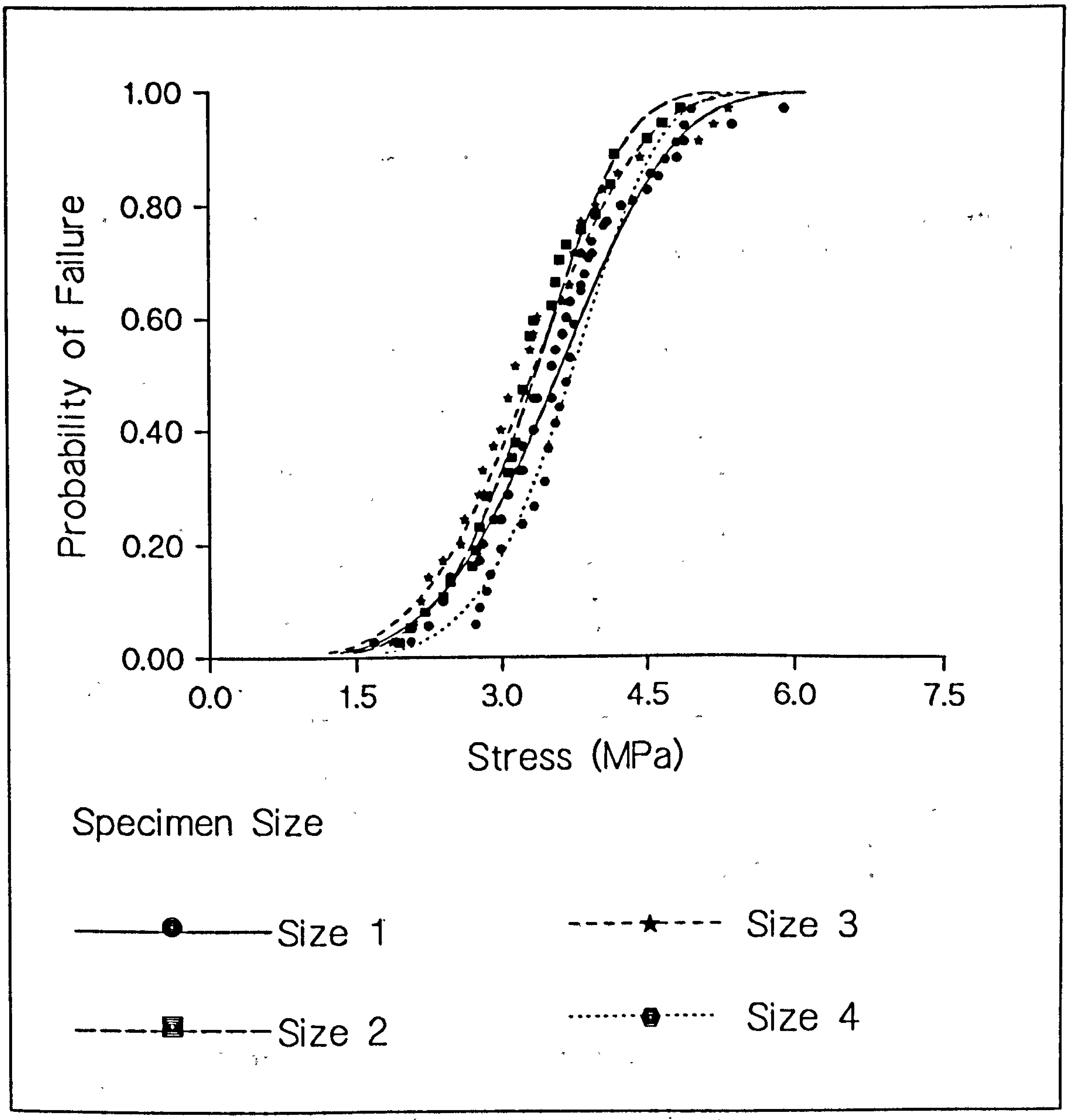


FIGURE 5.3.1.4

Diametral tensile strength of Plaster- Probability of failure versus diametral tensile stress of various specimen sizes at Crosshead Speed 0.1mm/min.

Size 1 = 18mm diameter by 10mm length, size 2 = 18mm diameter by 15mm length, size 3 = 18mm diameter by 20mm length and size 4 = 18mm diameter by 25mm length.

TABLE 5.3.1.5

Summary of Weibull Analysis-Diametral Tensile Strength of Plaster of Specimen Size 1* which is tested at various crosshead speed.

Crosshead Speed (mm/min)	0.1	0.5	1	10
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	4.3 3.9 0.12 0.97	4.0 3.4 0.13 0.97	4.7 3.3 0.09 0.99	5.2 3.2 0.14 0.98
Mean Strength+ Deviation Coefficient (%)	3.5 24.9	3.0 24.9	3.0 22.0	2.9 19.6
Stress+ at Failure Probability				
0.01% - Weibull Normal	0.5 2.91	0.3 2.5	0.5 2.55	0.5 2.52
1% - Weibull Normal	1.3 3.13	1.1 2.68	1.2 2.72	1.3 2.66
99.99% - Weibull Normal	5.5 4.09	4.9 3.5	4.6 3.28	4.2 3.28

* Size 1 = 18mm diameter by 10mm length.
+ unit in Mpa.
Oneway analysis of variance-Significant difference between compressive strength and crosshead speed ($P<0.05$).

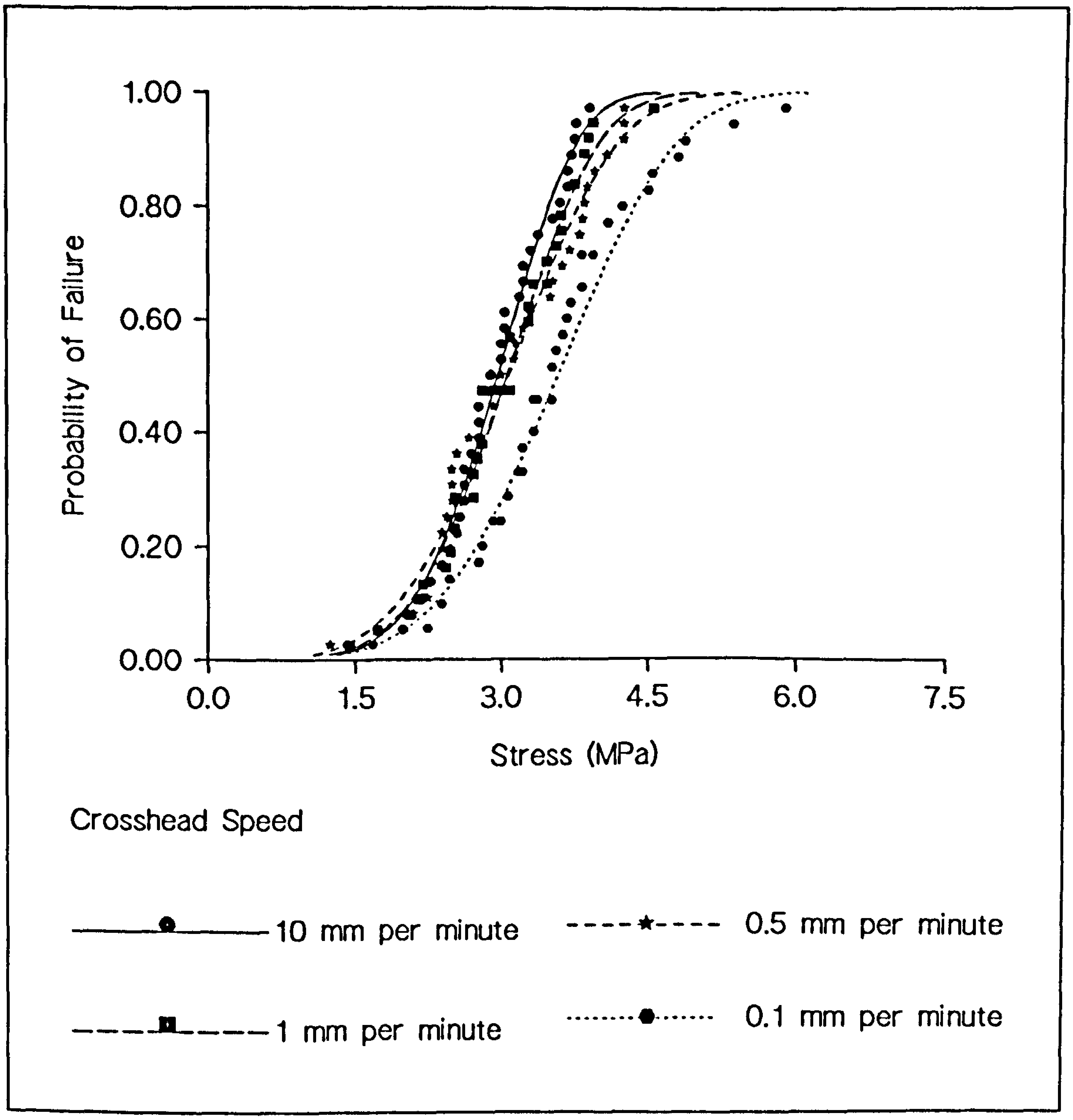


FIGURE 5.3.1.5

Diametral Tensile Strength of Plaster-Probability of Failure Versus Stress for SpecimenSize 1 which is tested with various crosshead speeds.

Size 1 = 18mm diameter by 10mm length.

TABLE 5.3.1.6

Summary of Weibull Analysis-Diametral Tensile Strength of Plaster of Specimen Size 2* which is tested at various crosshead speed.

Crosshead Speed (mm/min)		10	1	0.5	0.1
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation		6.9 3.3 0.23 0.97	6.2 3.3 0.18 0.97	6.1 3.5 0.16 0.98	5.2 3.6 0.13 0.98
Mean Strength+ Deviation Coefficient (%)		3.1 15.5	3.1 17.1	3.2 17.7	3.3 20.9
Stress+ at Failure Probability					
0.01%	- Weibull Normal	0.9 2.78	0.8 2.74	0.8 2.83	0.6 2.83
1%	- Weibull Normal	1.7 2.9	1.6 2.87	1.6 2.96	1.5 3.01
99.99%	- Weibull Normal	4.2 3.42	4.3 3.46	4.4 3.58	4.8 3.77

* Size 2 = 18mm diameter by 15mm length.
+ unit in Mpa.
Oneway analysis of variance-Highly no significant difference between compressive strength and crosshead speed (P=0.45).

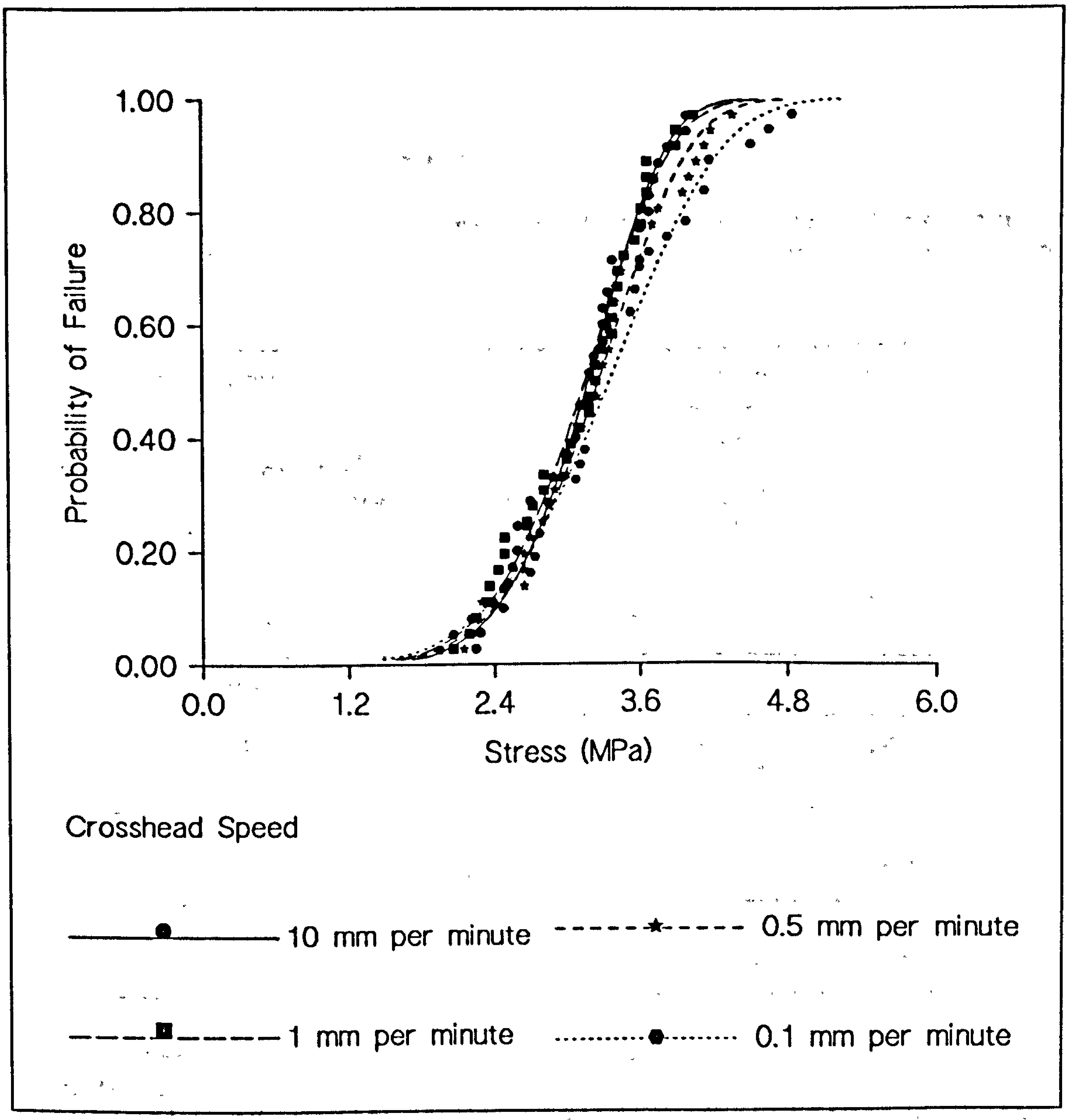


FIGURE 5.3.1.6

Diametral Tensile Strength of Plaster-Probability of Failure Versus Stress for SpecimenSize 2 which is tested with various crosshead speeds.

Size 2 = 18mm diameter by 15mm length.

TABLE 5.3.1.7

Summary of Weibull Analysis-Diametral Tensile Strength of Plaster of Specimen Size 3* which is tested at various crosshead speed.

Crosshead Speed (mm/min)	10	1	0.5	0.1
Weibull Modulus	8.8	6.67	6.4	4.2
Characteristic Strength+	3.1	3.6	3.5	3.6
Standard Error of Modulus	0.26	0.18	0.34	0.16
Coeff. of Correlation	0.97	0.98	0.92	0.95
Mean Strength+	2.9	3.4	3.2	3.3
Deviation Coefficient (%)	12.5	16.0	17.4	26.2
Stress+ at Failure Probability				
0.01% - Weibull	1.1	0.9	0.8	0.4
Normal	2.66	3.03	2.82	2.72
1% - Weibull	1.8	1.8	1.7	1.2
Normal	2.75	3.17	2.96	2.93
99.99% - Weibull	3.7	4.6	4.6	5.2
Normal	3.14	3.77	3.58	3.88

* Size 3 = 18mm diameter by 20mm length.
+ unit in Mpa.
Oneway analysis of variance-No significant difference between compressive strength and crosshead speed (P>0.05).

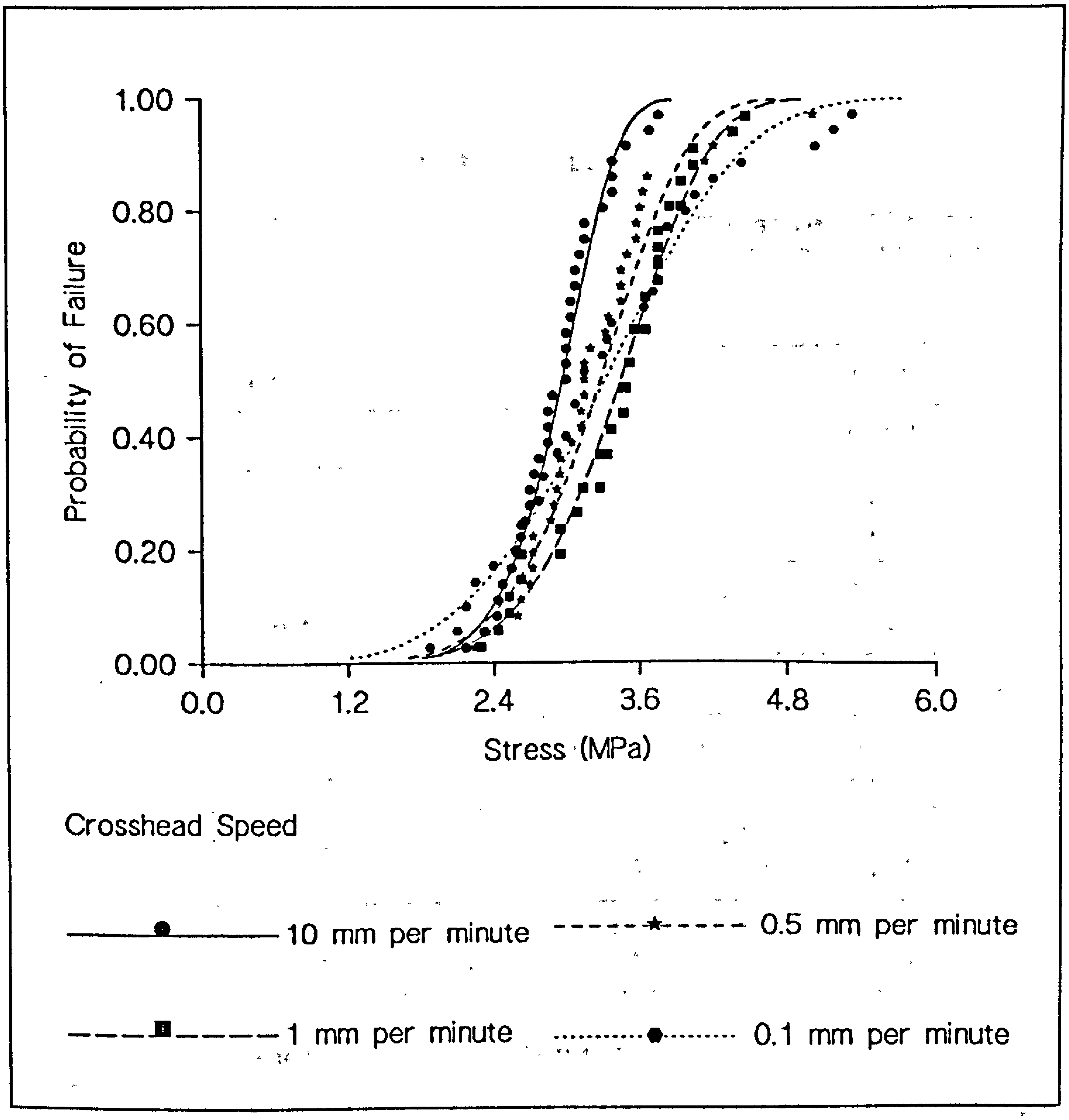


FIGURE 5.3.1.7

Diametral Tensile Strength of Plaster-Probability of Failure Versus Stress for SpecimenSize 3 which is tested with various crosshead speeds.

Size 3 = 18mm diameter by 20mm length.

TABLE 5.3.1.8

Summary of Weibull Analysis-Diametral Tensile Strength of Plaster of Specimen Size 4* which is tested at various crosshead speed.

Crosshead Speed (mm/min)	0.1	0.5	1.0	10.0
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	4.8 3.1 0.14 0.97	4.6 3.7 0.10 0.99	4.1 3.5 0.09 0.99	5.97 4.0 0.20 0.96
Mean Strength+ Deviation Coefficient (%)	2.9 21.6	3.4 22.2	3.2 24.9	3.7 18.0
Stress+ at Failure Probability				
0.01% - Weibull Normal	0.5 3.25	0.5 2.66	0.4 2.89	0.8 2.78
1% - Weibull Normal	1.2 3.42	1.4 2.86	1.1 3.08	1.8 2.83
99.99% - Weibull Normal	4.3 4.15	5.2 3.74	5.1 3.91	5.1 3.01

* Size 4 = 18mm diameter by 25mm length.
+ unit in Mpa.
Oneway analysis of variance-Very highly significant difference between compressive strength and crosshead speed (P<0.01).

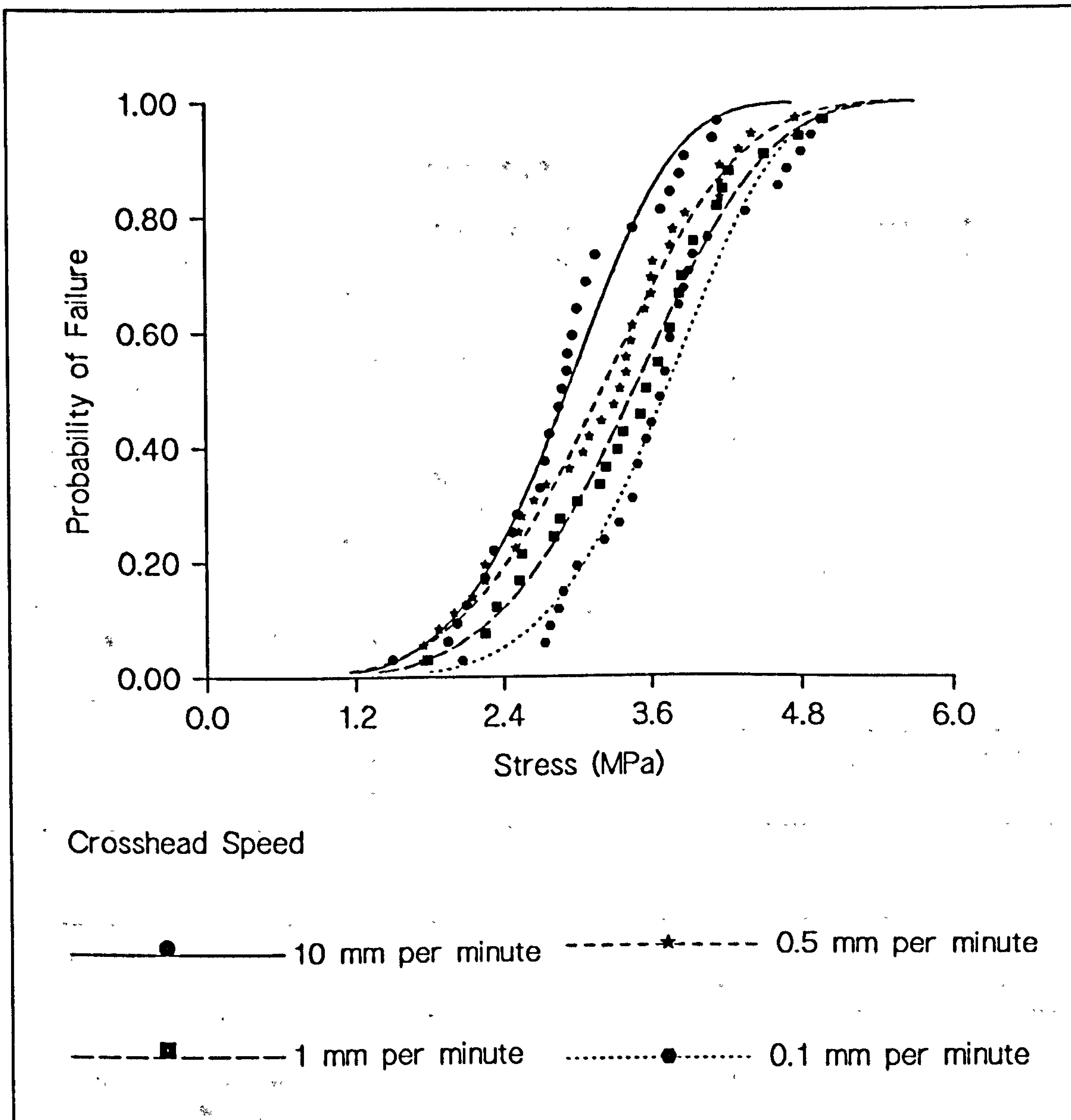


FIGURE 5.3.1.8

Diametral Tensile Strength of Plaster-Probability of Failure Versus Stress for SpecimenSize 4 which is tested with various crosshead speeds.

TABLE 5.3.2.1

Summary of Weibull analysis-Diametral tensile strength of Opalux tested at various crosshead speed for the specimens of Diameter/Length ratio 3:2*.

Crosshead Speed (mm/min)	0.1	0.5	1	10
Weibull Modulus	13.0	12.5	15.7	12.7
Characteristic Strength+	48.0	46.4	50.6	51.9
Standard Error of Modulus	0.64	0.40	0.40	0.78
Coeff. of Correlation	0.94	0.97	0.98	0.92
Mean Strength+	46.3	47.5	49.1	50.0
Deviation Coefficient (%)	8.3	8.6	6.9	8.6
Stress+ at Failure Probability				
0.01% - Weibull	23.6	23.7	28.1	24.5
Normal	43.7	44.7	46.8	47.1
1% - Weibull	33.7	24.2	37.8	35.7
Normal	44.7	45.8	47.6	48.2
99.99% - Weibull	54.0	55.8	55.8	58.8
Normal	48.9	50.2	51.4	52.9

* Specimen size 3mm diameter by 2mm length.
+ unit in Mpa.
Oneway analysis of variance-No significant difference between strength and crosshead speed (P>0.05).

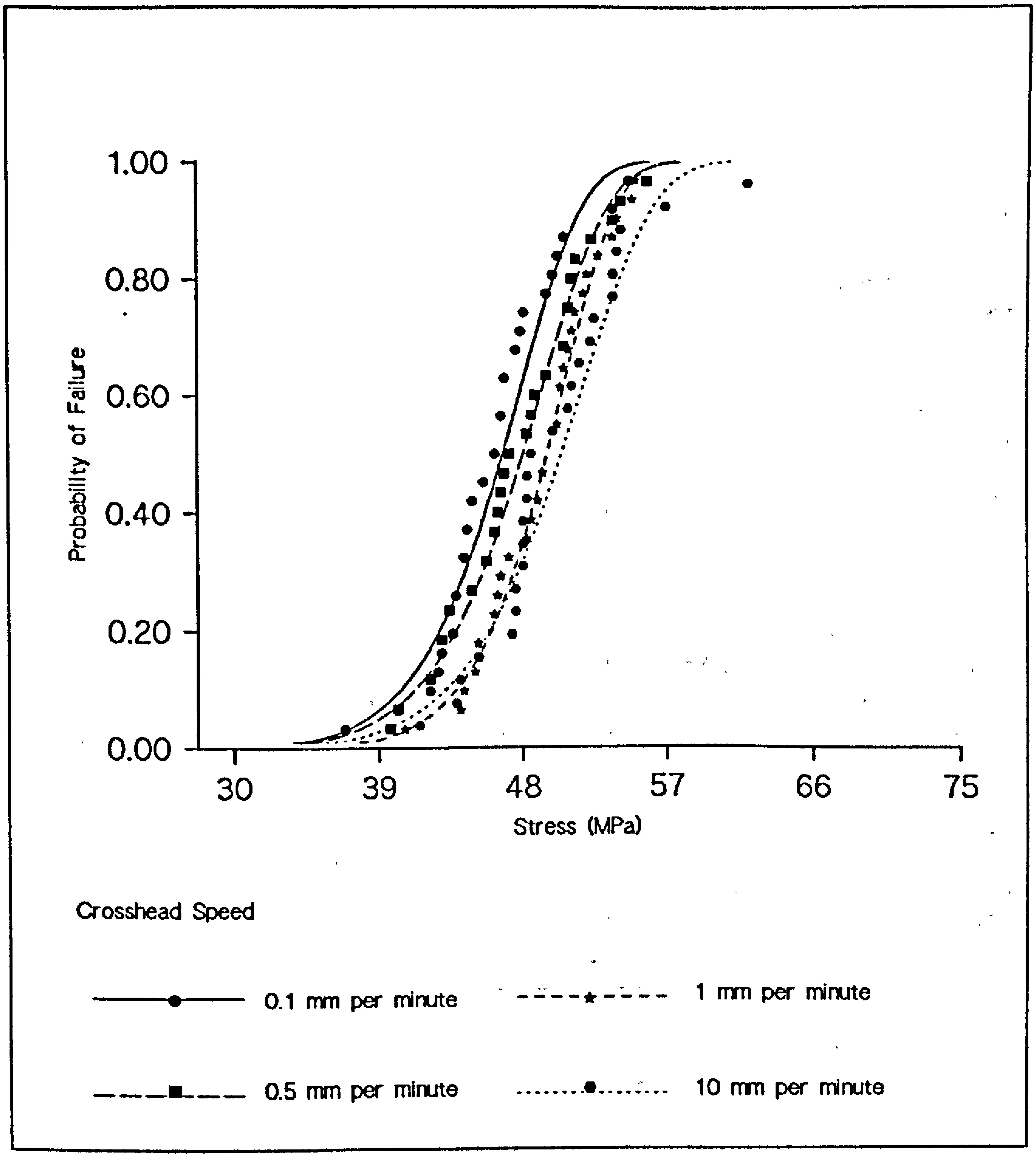


FIGURE 5.3.2.1

Diametral tensile strength of Opalux-Probability of failure versus diametral tensile stress tested at various crosshead speed for the specimens of Diameter/Length Ratio 3:2.

Specimen size 3mm diameter by 2mm length.

TABLE 5.3.2.2

Summary of Weibull analysis-Diametral tensile strength of Opalux tested at various crosshead speed for the specimens of Diameter/Length ratio 4:3*.

Specimen Diameter (mm)		0.1	0.5	1	10
Weibull Modulus		20.4	15.9	12.2	12.4
Characteristic Strength+		44.6	47.9	47.8	48.0
Standard Error of Modulus		0.68	0.59	0.41	0.36
Coeff. of Correlation		0.97	0.96	0.97	0.98
Mean Strength+		43.5	46.5	45.9	46.2
Deviation Coefficient (%)		5.3	6.7	8.9	8.6
Stress+ at Failure Probability					
0.01%	- Weibull	28.4	26.8	22.4	22.9
	Normal	41.9	44.4	43.1	43.5
1%	- Weibull	35.6	35.9	32.7	33.1
	Normal	42.5	45.2	44.2	44.5
99.99%	- Weibull	48.1	52.8	54.2	54.3
	Normal	45.1	48.6	48.7	48.9

* Specimen size 4mm diameter by 3mm length.
\+ unit in Mpa.
Oneway analysis of variance-Highly significant difference between strength and crosshead speed (P<0.01).

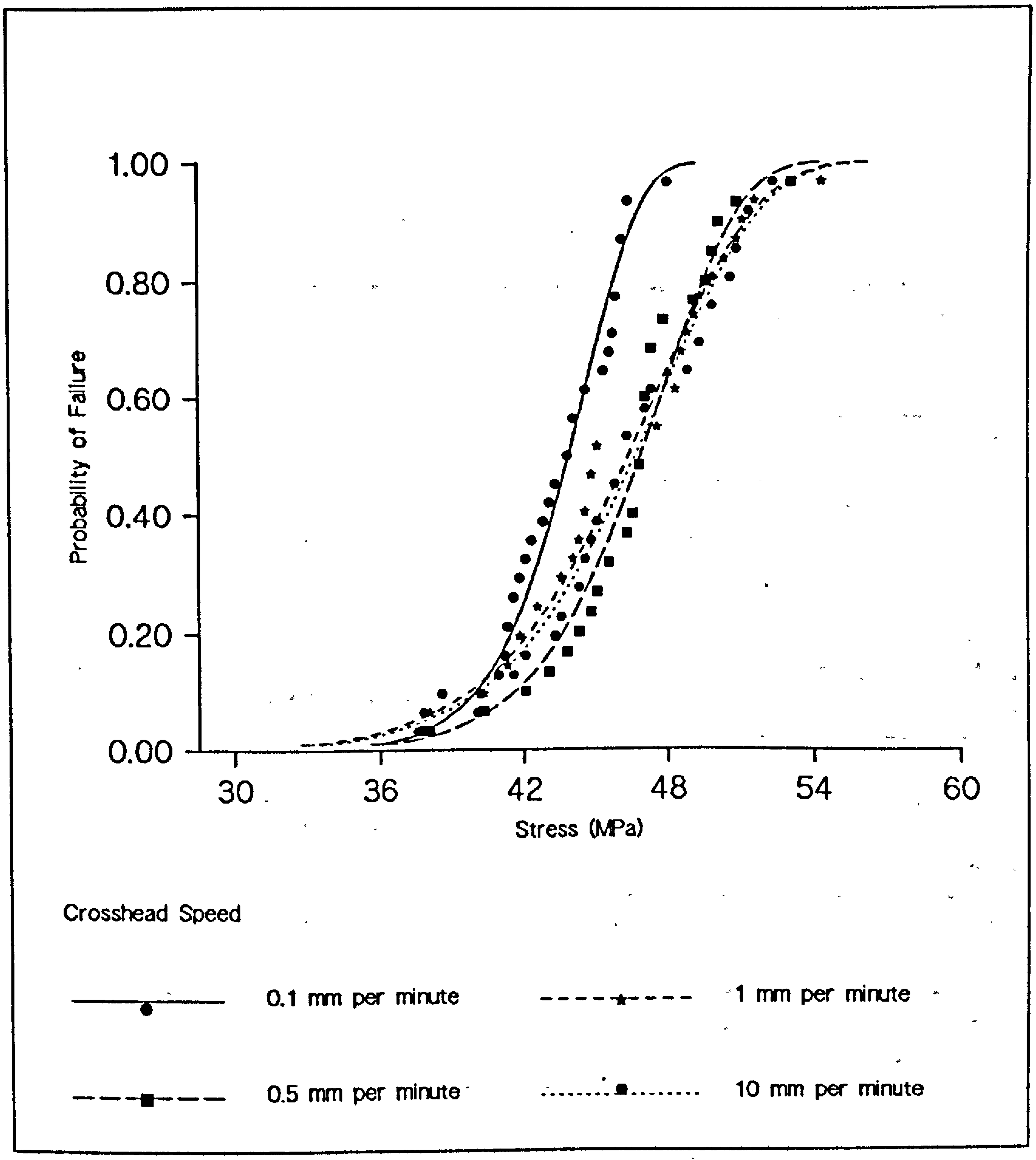


FIGURE 5.3.2.2

Diametral Tensile Strength of Opalux-Probability of Failure Versus Compressive Stress Tested at Various Crosshead Speed forSpecimens of Diameter/Length Ratio 4:3 .

Specimen size 4mm diameter by 3mm length.

TABLE 5.3.2.3

Summary of Weibull analysis-Diametral tensile strength of Opalux tested at various crosshead speed for the specimens of Diameter/Length ratio 1:1*.

Specimen Diameter (mm)		0.1	0.5	1	10
Weibull Modulus		14.1	12.5	10.8	9.4
Characteristic Strength		46.4	49.4	49.0	50.4
Standard Error of Modulus		0.50	0.56	0.21	0.38
Coeff. of Correlation		0.97	0.95	0.99	0.96
Mean Strength+		44.8	47.5	46.9	47.9
Deviation Coefficient (%)		7.5	8.2	9.8	11.3
Stress+ at Failure Probability					
0.01%	- Weibull	24.2	23.6	20.8	19.0
	Normal	42.5	44.9	43.8	44.2
1%	- Weibull	33.5	34.1	32.0	30.9
	Normal	43.4	45.8	44.9	45.6
99.99%	- Weibull	51.7	55.8	56.5	59.2
	Normal	47.1	50.1	50.0.	51.6

* Specimen size 4mm diameter by 4mm length.
\+ unit in Mpa.
Oneway analysis of variance-No significant difference between strength and crosshead speed (P>0.05).

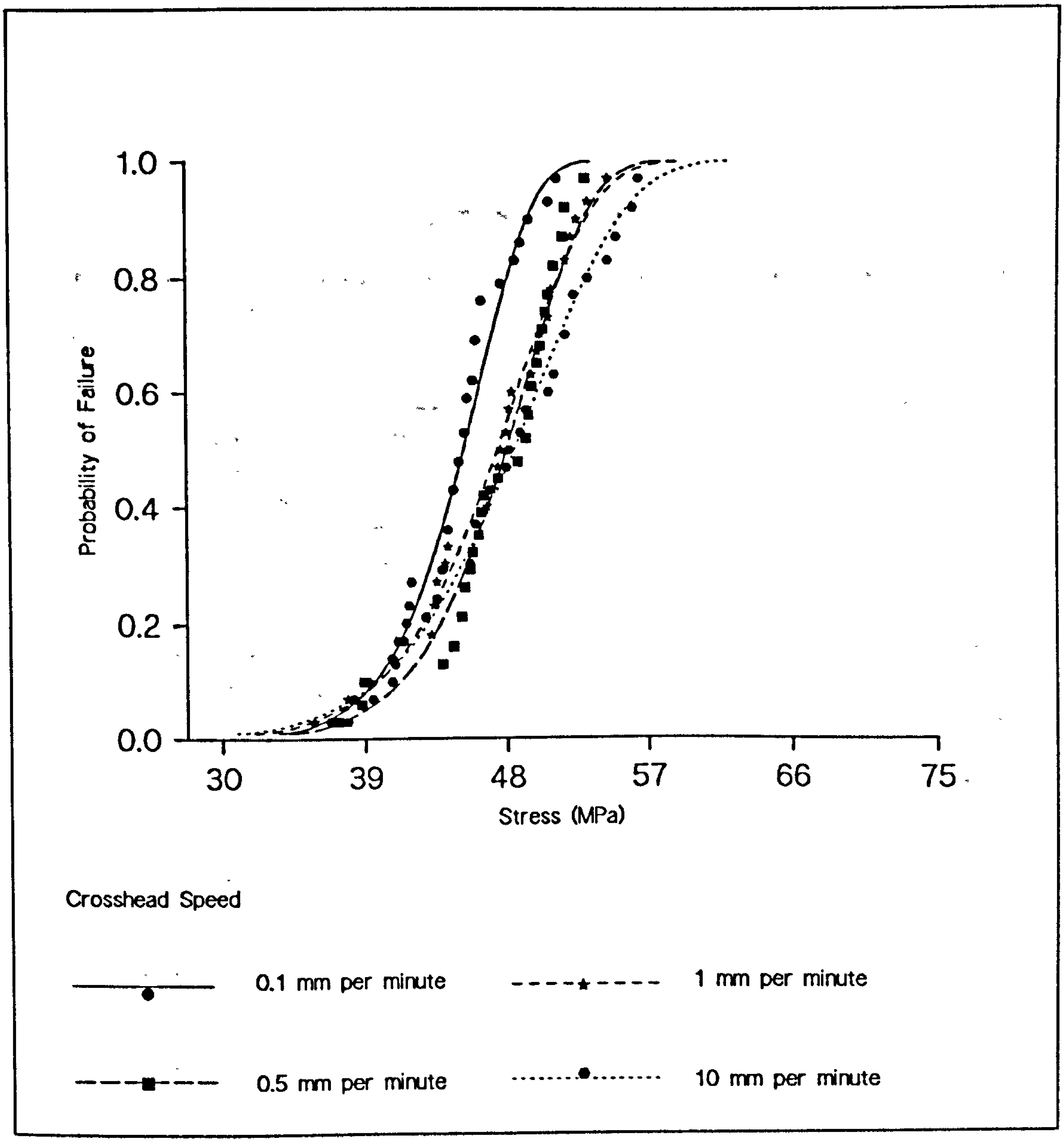


FIGURE 5.3.2.3

Diametral tensile strength of Opalux-Probability of failure versus diametral tensile stress tested at various crosshead speed for the specimens of Diameter/Length ratio 1:1.

Specimen size 4mm diameter by 4mm length.

TABLE 5.3.2.4

Summary of Weibull analysis-Diametral tensile strength of Opalux tested at various crosshead speed for the specimens of Diameter/Length ratio 1:1*.

Crosshead Speed (mm/min)	0.1	0.5	1	10
Weibull Modulus	12.9	9.3	11.2	9.4
Characteristic Strength	46.5	49.6	49.7	48.1
Standard Error of Modulus	0.60	0.29	0.25	0.35
Coeff. of Correlation	0.94	0.98	0.99	0.98
Mean Strength+	44.8	47.1	47.6	45.7
Deviation Coefficient (%)	8.3	11.1	9.4	11.0
Stress+ at Failure Probability				
0.01% - Weibull	22.8	18.5	21.8	18.0
Normal	42.3	43.6	44.6	42.3
1% - Weibull	32.6	31.0	33.0	29.4
Normal	43.2	44.9	45.7	43.6
99.99% - Weibull	52.4	58.4	57.0	56.6
Normal	47.3	50.6	50.6	49.1

* Specimen size 5mm diameter by 5mm length.
\+ unit in Mpa.
Oneway analysis of variance-No significant difference between strength and crosshead speed (P>0.05).

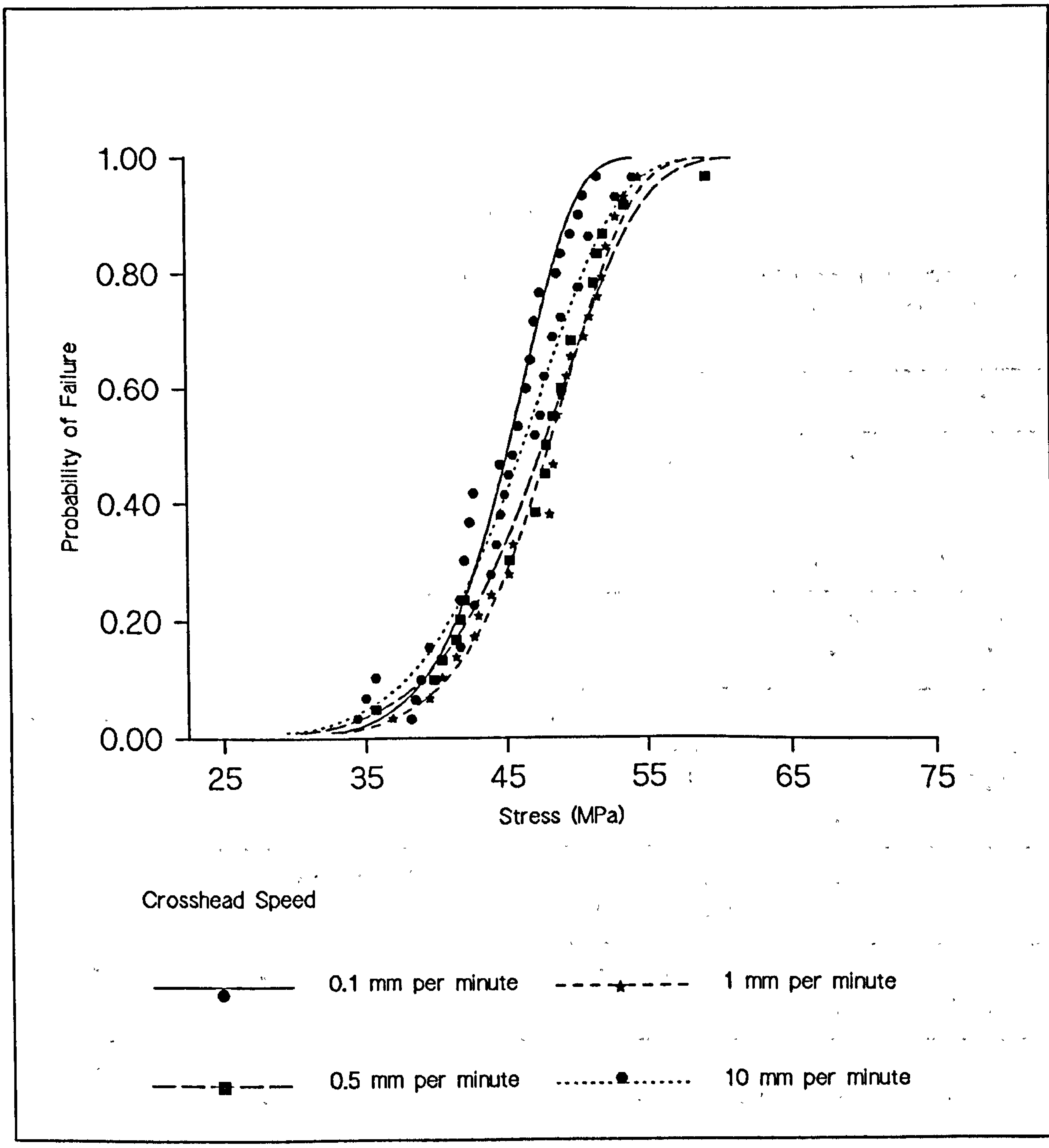


FIGURE 5.3.2.4

Diametral tensile strength of Opalux-Probability of failure versus diametral tensile stress tested at various crosshead speed for the specimens of Diameter/Length ratio 1:1.

Specimen size 5mm diameter by 5mm length.

TABLE 5.3.2.5

Summary of Weibull analysis-Diametral tensile strength of Opalux tested at crosshead speed 0.1mm/min for the specimens of various Diameter/Length ratios.

Diameter/Length Ratios	3:2	4:3	4:4	5:5
Weibull Modulus	13.0	20.4	14.1	12.9
Characteristic Strength+	48.0	44.6	46.4	46.5
Standard Error of Modulus	0.64	0.68	0.50	0.60
Coeff. of Correlation	0.94	0.97	0.97	0.94
Mean Strength+	46.3	43.5	44.8	44.8
Deviation Coefficient (%)	8.3	5.3	7.5	8.3
Stress+ at Failure Probability				
0.01% - Weibull	23.6	28.4	24.2	22.8
Normal	43.7	41.9	42.5	42.3
1% - Weibull	33.7	35.6	33.5	27.2
Normal	44.7	42.5	43.4	43.2
99.99% - Weibull	54.0	48.1	51.7	52.4
Normal	48.9	45.1	47.1	47.3

+ unit in Mpa.
Oneway analysis of variance-No significant difference between strength and Diameter/Length ratio (P>0.05).

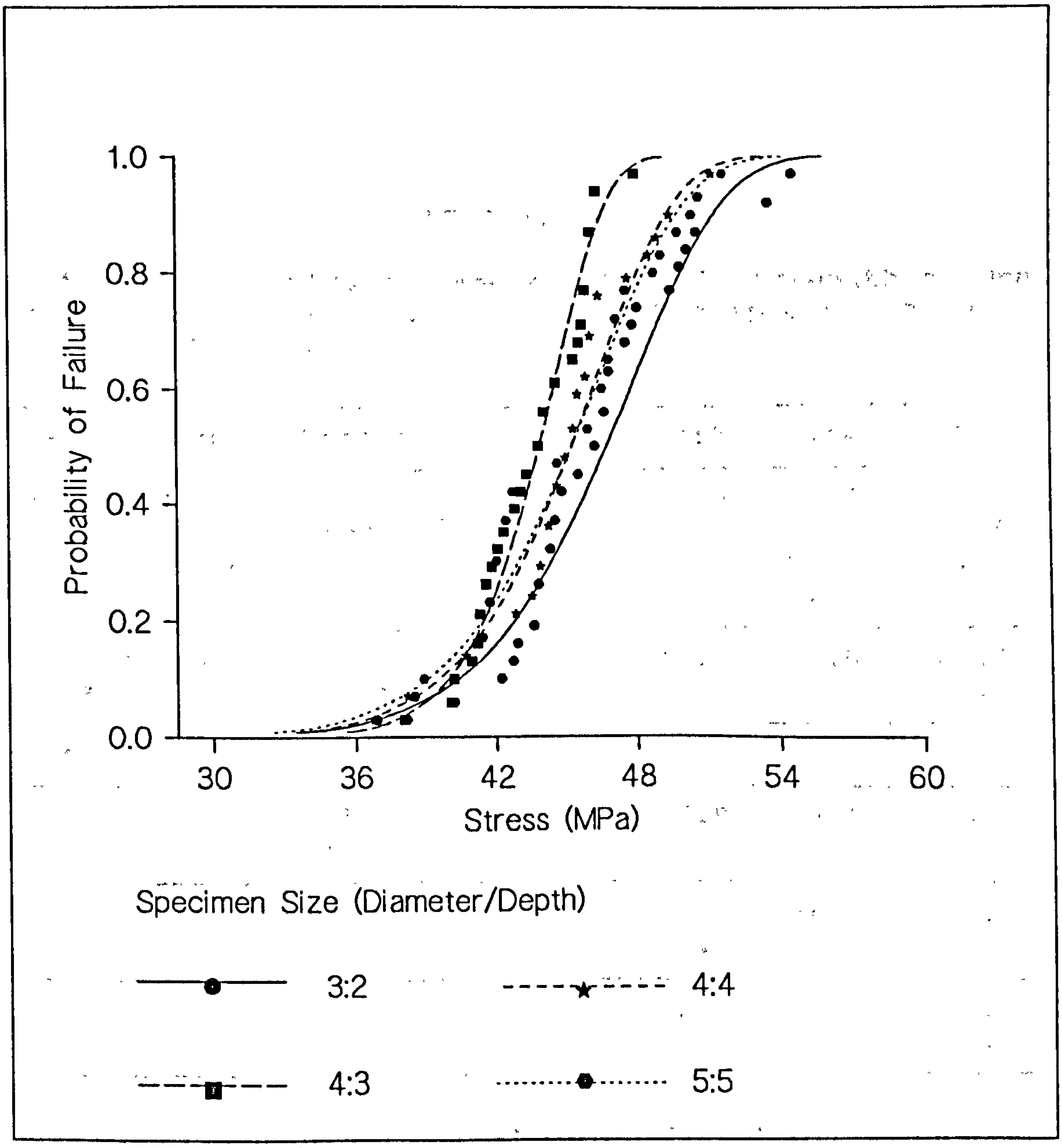


FIGURE 5.3.2.5

Diametral Tensile strength of Opalux-Probability of failure versus diametral tensile stress tested at crosshead speed 0.1mm/min for the specimens of various Diameter/ Length ratios.

TABLE 5.3.2.6

Summary of Weibull analysis-Diametral tensile strength of Opalux tested at crosshead speed 0.5mm/min for the specimen of various Diameter/Length ratios.

Diameter/Length Ratios	3:2	4:3	4:4	5:5
Weibull Modulus	12.5	15.9	12.5	9.3
Characteristic Strength+	49.4	47.9	49.4	49.6
Standard Error of Modulus	0.40	0.59	0.56	0.29
Coeff. of Correlation	0.97	0.96	0.95	0.98
Mean Strength+	47.5	46.5	47.5	47.1
Deviation Coefficient (%)	8.6	6.7	8.2	11.1
Stress+ at Failure Probability				
0.01% - Weibull	23.7	26.8	23.6	18.5
Normal	44.7	44.4	44.9	43.6
1% - Weibull	34.2	35.9	34.1	31.0
Normal	45.8	45.2	45.8	44.9
99.99% - Weibull	55.8	52.8	55.8	58.4
Normal	50.2	48.6	50.1	50.6

+ unit in Mpa.
Oneway analysis of variance-No significant difference between strength and Diameter/Length ratio (P>0.05).

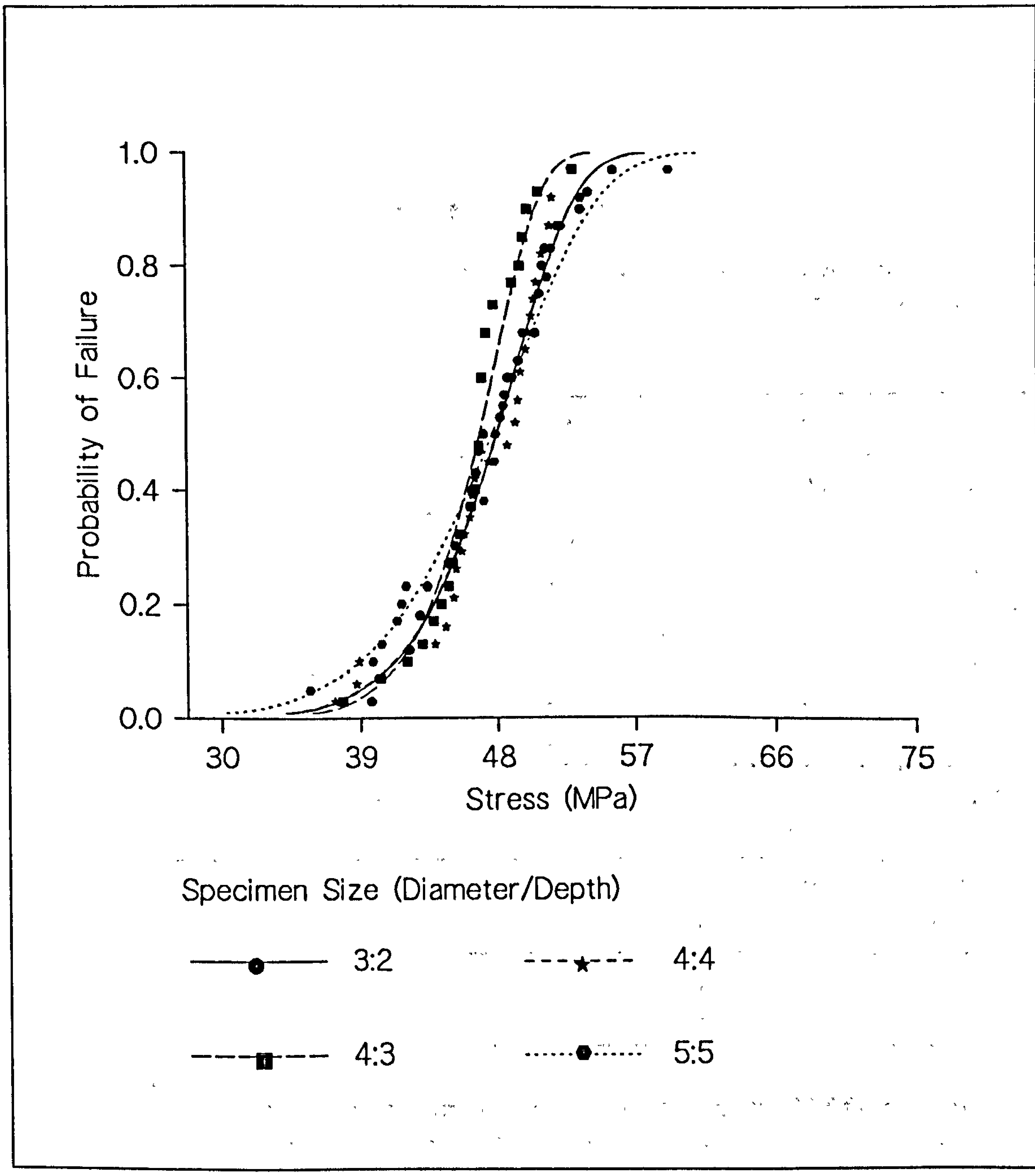


FIGURE 5.3.2.6

Diametral tensile strength of Opalux-Probability of failure versus diametral tensile stress tested at crosshead speed 0.5mm/min for the specimens of various Diameter/ Length ratios.

TABLE 5.3.2.7

Summary of Weibull analysis-Diametral tensile strength of Opalux tested at crosshead speed 1mm/min for the specimen of various Diameter/Length ratios.

Diameter/Length Ratio		3:2	4:3	4:4	5:5
Weibull Modulus		15.7	12.2	10.8	11.2
Characteristic Strength		50.6	47.8	49.0	49.7
Standard Error of Modulus		0.40	0.41	0.21	0.25
Coeff. of Correlation		0.98	0.97	0.99	0.99
Mean Strength+		49.1	45.9	46.9	47.6
Deviation Coefficient (%)		6.9	8.9	9.8	9.4
Stress+ at Failure Probability					
0.01%	- Weibull	28.1	22.4	20.8	21.8
	Normal	46.8	43.1	43.8	44.6
1%	- Weibull	37.8	32.7	32.0	26.8
	Normal	47.6	44.2	44.9	45.7
99.99%	- Weibull	55.8	54.2	56.5	57.0
	Normal	51.4	48.7	50.0	50.6

+ unit in Mpa.
Oneway analysis of variance-No significant difference between strength and Diameter/Length ratio ($P>0.05$).

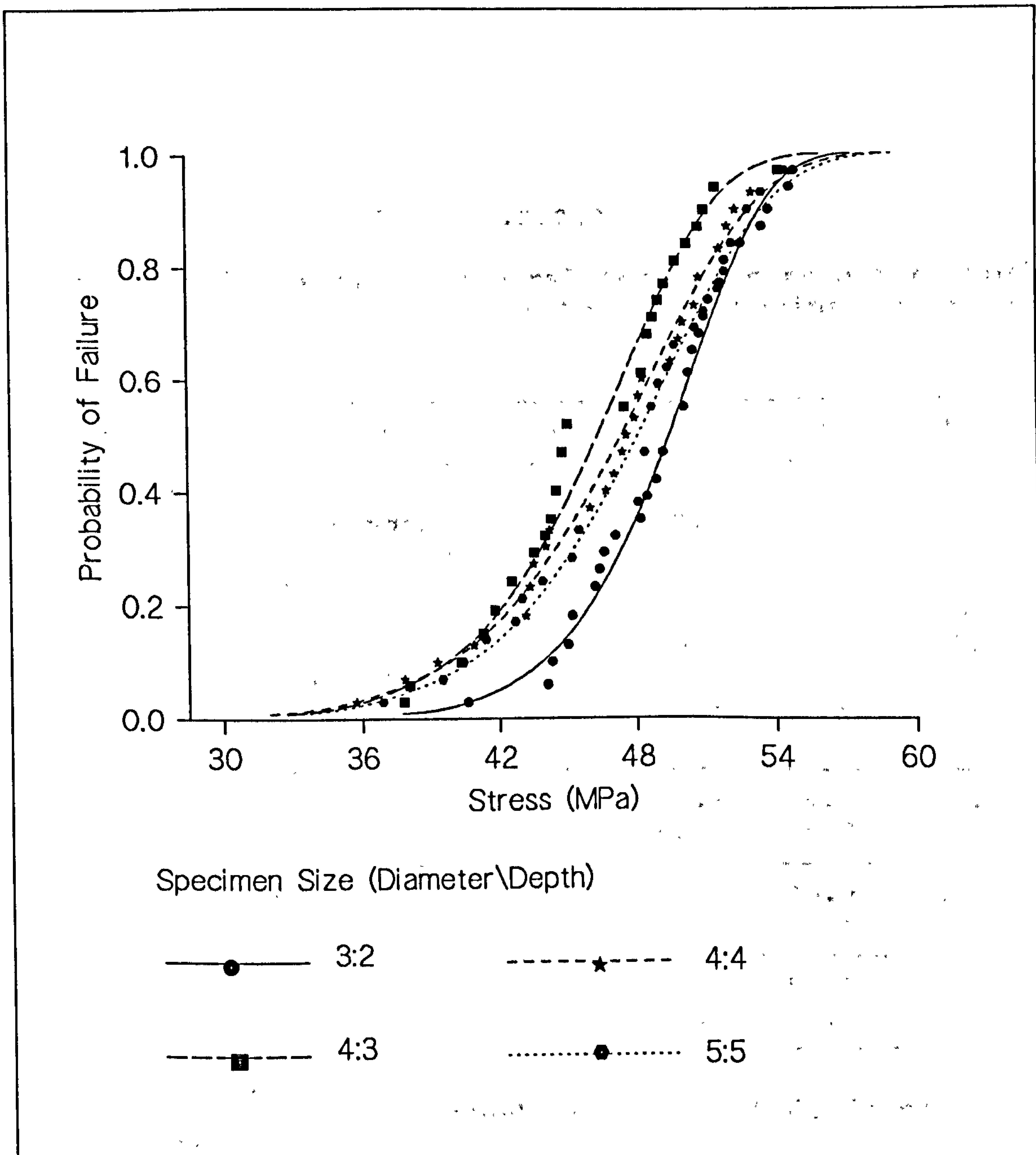


FIGURE 5.3.2.7

Diametral tensile strength of Opalux-Probability of failure versus diametral tensile stress tested at crosshead speed 1mm/min for the specimens of various Diameter/Length ratios.

TABLE 5.3.2.8

Summary of Weibull analysis-Diametral tensile strength of Opalux tested at crosshead speed 10m/min for the specimen of various Diameter/Length ratios.

Diameter/Length Ratio	3:2	4:3	4:4	5:5
Weibull Modulus	12.3	12.4	9.4	9.4
Characteristic Strength+	51.9	48.0	50.4	48.1
Standard Error of Modulus	0.78	0.36	0.38	0.35
Coeff. of Correlation	0.92	0.98	0.96	0.98
Mean Strength+	50.0	46.2	47.9	45.7
Deviation Coefficient (%)	8.6	8.6	11.3	11.0
Stress+ at Failure Probability				
0.01% - Weibull	24.5	22.9	19.0	18.0
Normal	47.1	43.5	44.2	42.3
1% - Weibul	35.7	33.1	30.9	29.4
Normal	48.2	44.5	45.6	43.6
99.99% - Weibull	58.8	54.3	59.2	56.6
Normal	52.9	48.9	51.6	49.1

\+ unit in Mpa.
Oneway analysis of variance-No significant difference between strength and Diameter/Length ratio (P>0.05).

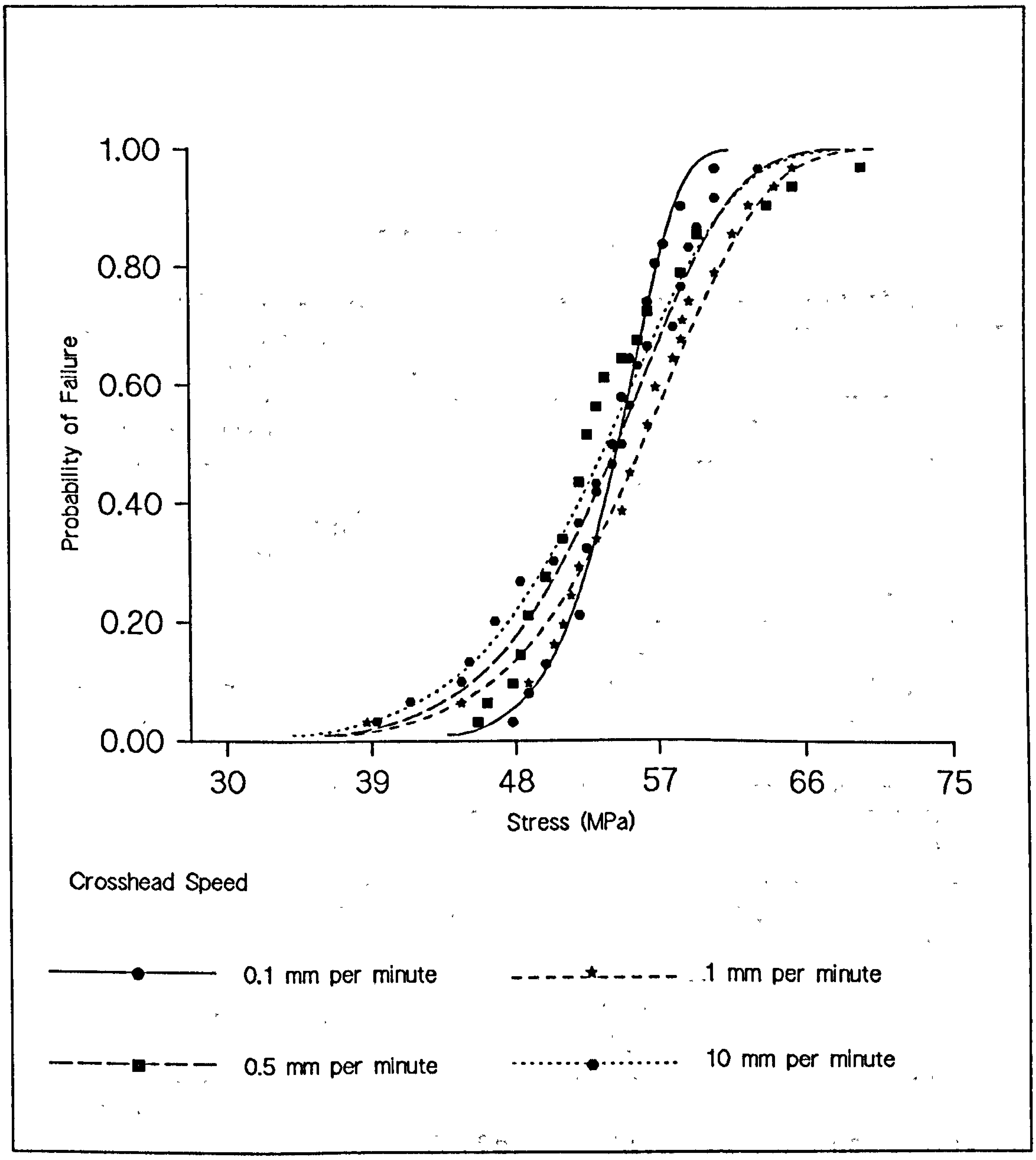


FIGURE 5.3.2.8

Diametral tensile strength of Opalux-Probability of failure versus diametral tensile stress tested at crosshead speed 10mm/min for the specimens of various Diameter/Length ratios.

TABLE 5.3.3.1

Summary of Weibull analysis-Diametral tensile strength of Occlusin tested at various crosshead speed for the specimens of 3mm diameter by 2mm length*.

Crosshead Speed (mm/min)		0.1	0.5	1	10
Weibull Modulus		19.3	10.3	10.1	9.3
Characteristic Strength+		55.5	56.3	58.0	55.8
Standard Error of Modulus		0.62	0.79	0.35	0.19
Coeff. of Correlation		0.97	0.86	0.97	0.99
Mean Strength+		54.1	53.8	55.4	53.1
Deviation Coefficient (%)		5.6	10.4	10.2	11.3
Stress+ at Failure Probability					
0.01%	- Weibull	34.5	23.0	23.4	20.8
	Normal	52.1	50.0	51.6	49.0
1%	- Weibull	43.7	36.0	36.8	34.1
	Normal	52.8	51.4	53.0	50.5
99.99%	- Weibull	60.1	65.4	67.5	65.8
	Normal	56.1	57.6	59.2	57.2

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing. Oneway analysis of variance-Highly no significant difference between strength and crosshead speed (P=0.42).

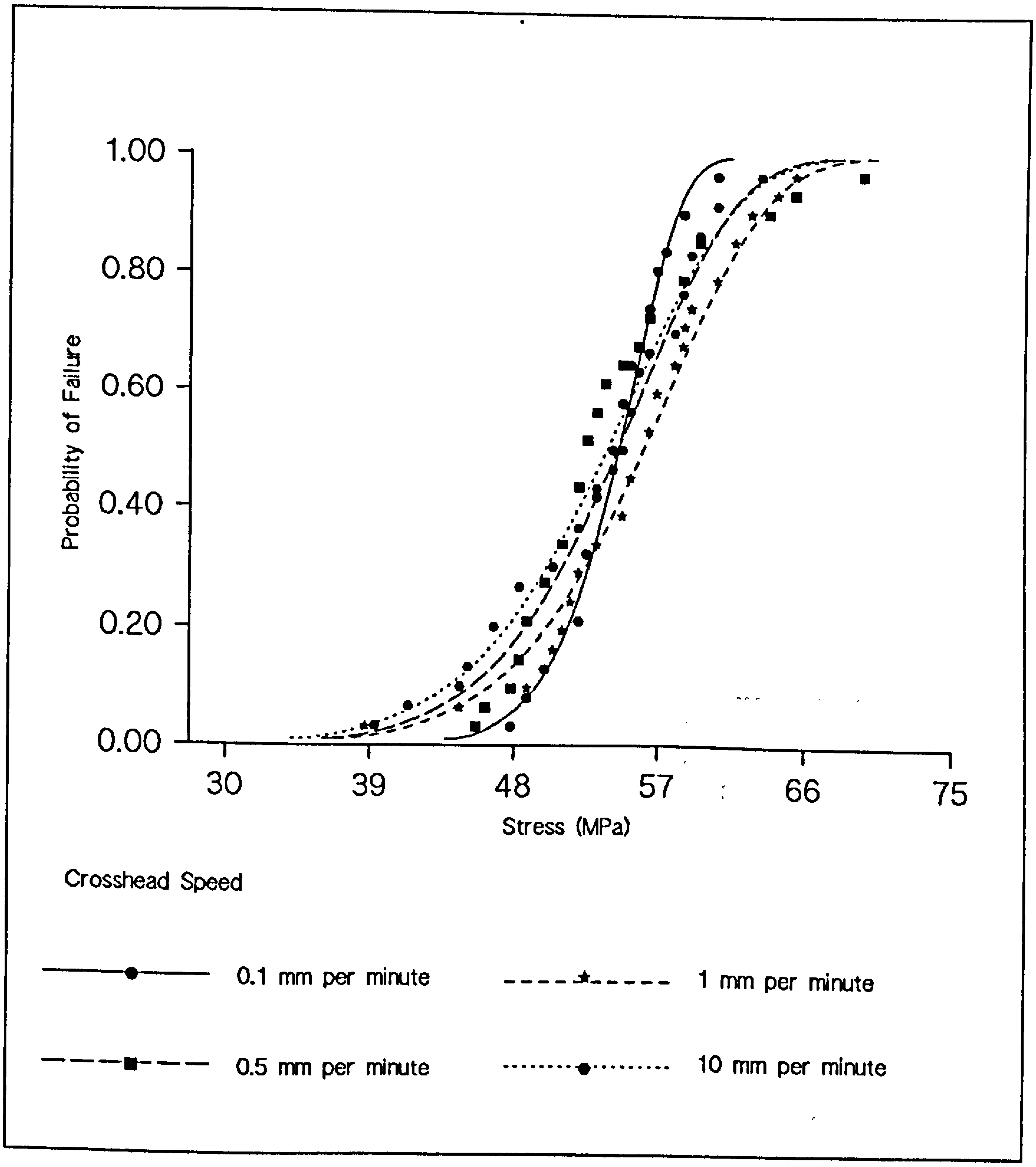


FIGURE 5.3.3.1

Diametral tensile Strength of Occlusin-Probability of failure versus diametral tensile stress tested at various crosshead speed for the specimens of 3mm diameter by 2mm Length.

Specimens are bench dried for 7 days prior testing.

TABLE 5.3.3.2

Summary of Weibull analysis-Diametral tensile strength of Occlusin tested at various crosshead speed for the specimens of 3mm diameter by 3mm length*.

Crosshead Speed (mm/min)	0.1	0.5	1	10
Weibull Modulus	10.7	11.0	8.7	9.4
Characteristic Strength+	51.8	47.6	50.0	48.9
Standard Error of Modulus	0.69	0.36	0.17	0.38
Coeff. of Correlation	0.90	0.97	0.99	0.96
Mean Strength+	49.5	45.5	47.4	46.5
Deviation Coefficient (%)	9.8	9.6	11.9	11.4
Stress+ at Failure Probability				
0.01% - Weibull	22.0	20.6	17.7	18.3
Normal	46.2	42.5	43.6	42.9
1% - Weibull	33.7	31.3	29.8	29.9
Normal	47.4	43.6	45.0	44.2
99.99.% - Weibull	59.7	54.6	59.4	57.6
Normal	52.8	48.5	51.2	50.1

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-No significant difference between strength and crosshead speed (P>0.05).

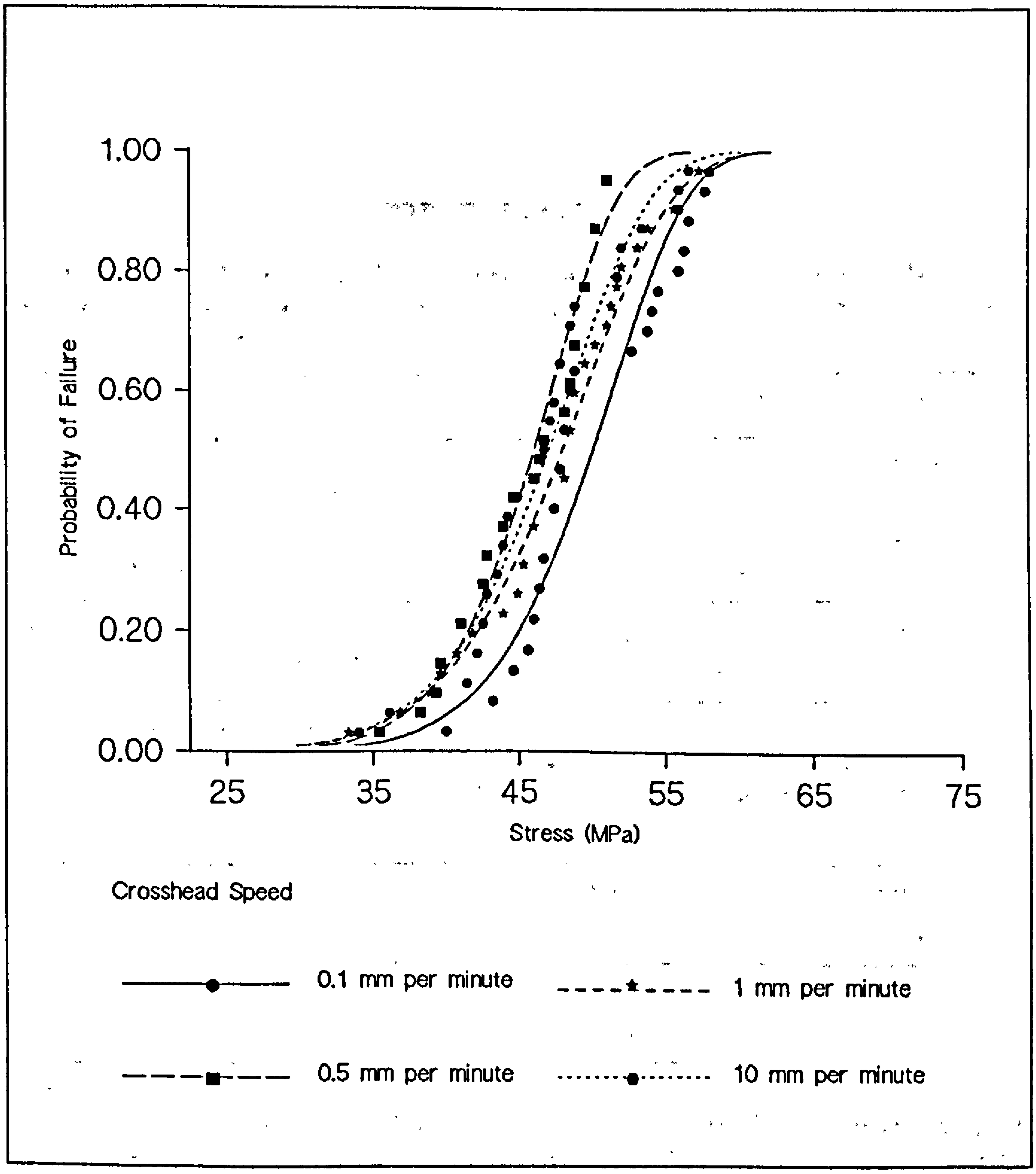


FIGURE 5.3.3.2
Diametral tensile strength of Occlusin-Probability of failure versus diametral tensile stress tested at various crosshead speed for the specimens of 3mm diameter by 3mm length.
Specimens are bench dried for 7 days prior testing.

TABLE 5.3.3.3

Summary of Weibull analysis-Diametral tensile strength of Occlusin tested at various crosshead speed for the specimens of 4mm diameter by 4mm length*.

Crosshead Speed (mm/min)		0.1	0.5	1	10
Weibull Modulus		15.5	18.2	22.9	15.4
Characteristic Strength+		49.5	49.1	51.4	50.3
Standard Error of Modulus		0.71	0.71	0.63	0.83
Coeff. of Correlation		0.95	0.96	0.98	0.93
Mean Strength+		47.9	47.8	50.3	48.7
Deviation Coefficient (%)		6.8	5.8	4.7	6.9
Stress+ at Failure Probability					
0.01%	- Weibull	27.3	29.6	34.4	27.7
	Normal	45.7	45.9	48.7	46.4
1%	- Weibull	36.8	38.1	42.0	37.3
	Normal	46.5	46.6	49.3	47.3
99.9%	- Weibull	54.6	53.4	55.0	55.6
	Normal	50.1	49.7	51.9	51.0

+ unit in Mpa.

* Specimens are bench dried for 7 days prior testing. Oneway analysis of variance-No significant difference between strength and crosshead speed (P>0.05).

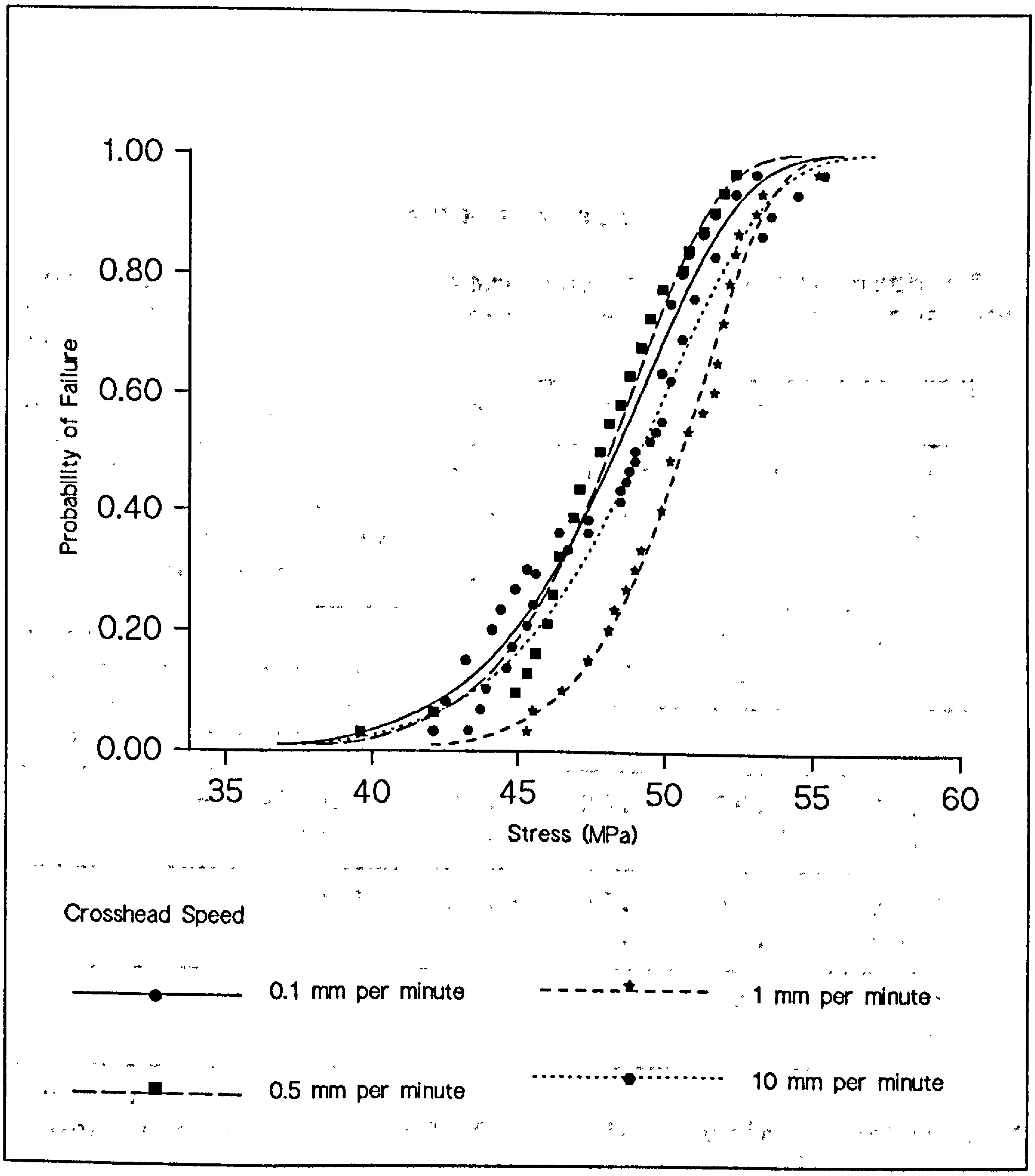


FIGURE 5.3.3.3
Diametral tensile strength of Occlusin-Probability of failure versus diametral tensile stress tested at various crosshead Speed for the specimens of 4mm Diameter by 4mm length.
Specimens are bench dried for 7 days prior testing.

TABLE 5.3.3.4

Summary of Weibull analysis-Diametral tensile strength of Occlusin tested at various crosshead speed for the specimens of 5mm diameter by 5mm length*.

Crosshead Speed (mm/min)	0.1	0.5	1	10
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	14.2 45.4 0.28 0.99	17.1 49.1 0.57 0.97	14.8 48.7 0.36 0.98	14.0 50.1 0.23 0.99
Mean Strength+ Deviation Coefficient (%)	43.8 7.6	47.7 6.3	47.1 7.2	48.3 7.7
Stress+ at Failure Probability				
0.01% - Weibull Normal	23.8 41.5	28.7 45.7	26.2 44.8	25.9 45.8
1% - Weibull Normal	32.9 42.4	37.5 46.4	35.7 45.6	36.0 46.7
99.99% - Weibull Normal	50.5 46.0	53.7 49.7	54.0 49.4	55.8 50.8

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing. Oneway analysis of variance-Very highly significant difference between strength and crosshead speed ($P<0.001$).

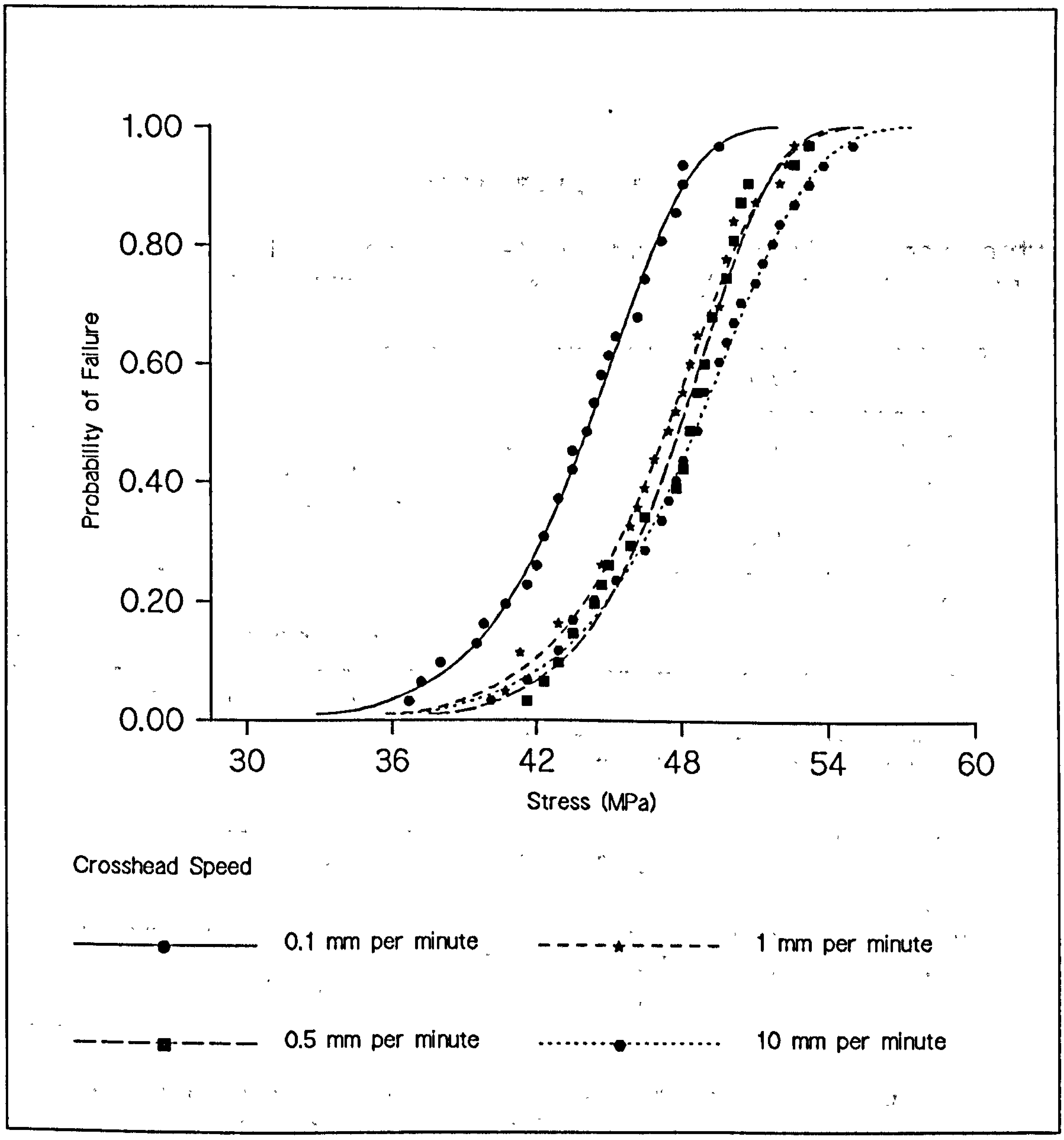


FIGURE 5.3.3.4
Diametral tensile strength of Occlusin-Probability of failure versus diametral tensile stress tested at various crosshead speed for the specimens of 5mm diameter by 5mm length.
Specimens are bench dried for 7 days prior testing.

TABLE 5.3.3.5

Summary of Weibull analysis-Diametral tensile strength of Occlusin tested at crosshead speed 0.1mm/min for the specimens of various diameter/length ratios.

Diameter/Length Ratios	3:2	3:3	4:4	5:5
Weibull Modulus	19.3	10.7	15.5	14.2
Characteristic Strength+	55.5	51.8	49.5	45.4
Standard Error of Modulus	0.62	0.69	0.71	0.28
Coeff. of Correlation	0.97	0.90	0.95	0.99
Mean Strength+	54.1	49.5	47.9	43.8
Deviation Coefficient (%)	5.6	9.8	6.8	7.6
Stress+ at Failure Probability				
0.01% - Weibull	34.5	22.0	27.3	23.8
Normal	52.1	46.2	45.7	41.5
1% - Weibull	43.7	33.7	36.8	32.9
Normal	52.8	47.4	46.5	42.4
99.99% - Weibull	60.1	59.7	54.6	50.5
Normal	56.1	52.8	50.1	46.0

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-Very highly significant difference between strength and specimen size (P<0.001).

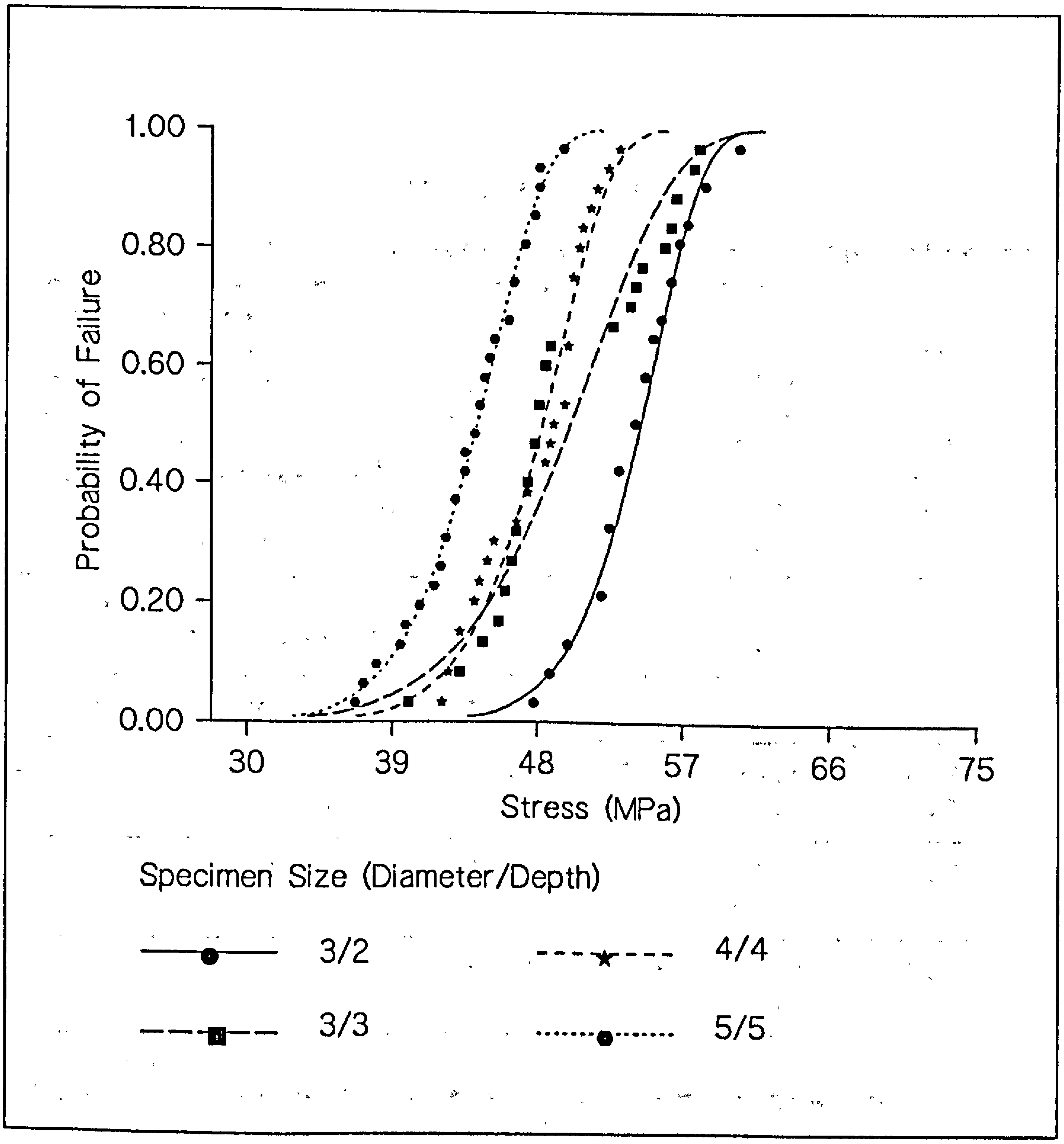


FIGURE 5.3.3.5
Diametral tensile strength of Occlusin-Probability of failure versus diametral tensile stress tested at crosshead speed 0.1mm/min for the specimens of various diameter/length ratios.
Specimens are bench dried for 7 days prior testing.

TABLE 5.3.3.6

Summary of Weibull analysis-Diametral tensile strength of Occlusin tested at crosshead speed 0.5mm/min for the specimens of various diameter/length ratios.

Diameter/Length Ratios	3:2	3:3	4:4	5:5
Weibull Modulus	10.3	11.0	18.2	17.1
Characteristic Strength+	56.3	47.6	49.1	49.1
Standard Error of Modulus	0.79	0.36	0.71	0.57
Coeff. of Correlation	0.86	0.97	0.96	0.97
Mean Strength+	53.8	45.5	47.8	47.7
Deviation Coefficient (%)	10.4	9.6	5.8	6.3
Stress+ at Failure Probability				
0.01% - Weibull	23.0	20.6	29.6	28.7
Normal	50.0	42.5	45.9	45.7
1% - Weibull	36.0	31.3	38.1	37.5
Normal	51.4	43.6	46.6	46.4
99.99% - Weibull	65.4	54.6	53.4	53.7
Normal	57.6	48.5	49.7	49.7

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-Very highly significant difference between strength and crosshead speed (P<0.001).

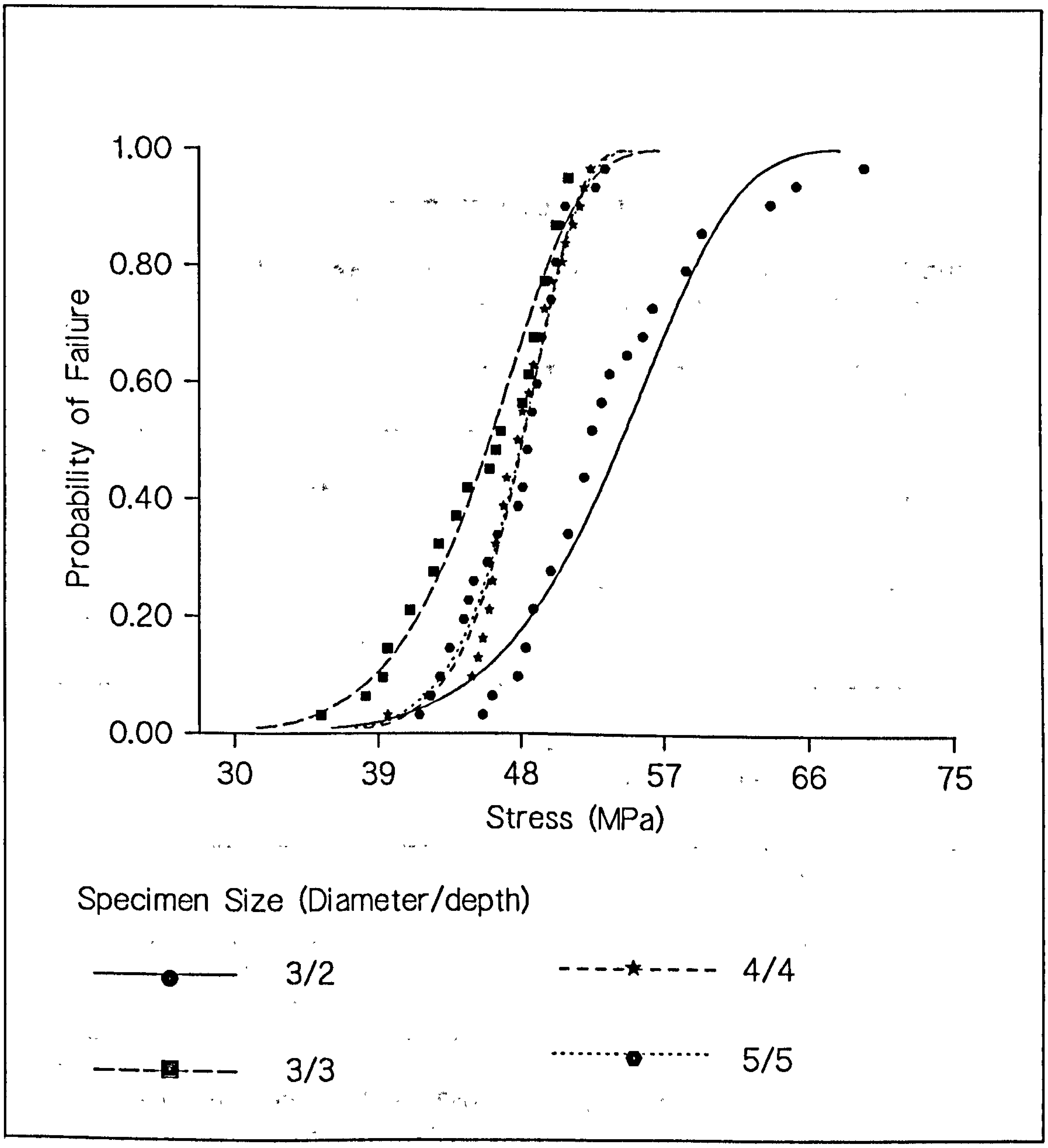


FIGURE 5.3.3.6

Diametral tensile strength of Occlusin-Probability of failure versus diametral tensile stress tested at crosshead speed 0.5mm/min for the specimens of various diameter/length ratios.

Specimens are bench dried for 7 days prior testing.

TABLE 5.3.3.7

Summary of Weibull analysis-Diametral tensile strength of Occlusin tested at crosshead speed 1mm/min for the specimens of various diameter/length ratios.

Diameter/Length Ratios		3:2	3:3	4:4	5:5
Weibull Modulus		10.1	8.7	22.9	14.8
Characteristic Strength+		58.0	50.0	51.4	48.7
Standard Error of Modulus		0.35	0.17	0.63	0.36
Coeff. of Correlation		0.97	0.99	0.98	0.98
Mean Strength+		55.4	47.4	50.3	47.1
Deviation Coefficient (%)		10.2	11.9	4.7	7.2
Stress+ at Failure Probability					
0.01%	- Weibull	23.4	17.7	34.4	26.2
	Normal	51.6	43.6	48.7	44.8
1%	- Weibull	36.8	29.8	42.0	35.7
	Normal	53.0	45.0	49.3	45.6
99.99%	- Weibull	67.5	59.4	55.0	54.0
	Normal	59.2	51.2	51.9	49.4

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-Very highly significant difference between strength and specimen size (P<0.001).

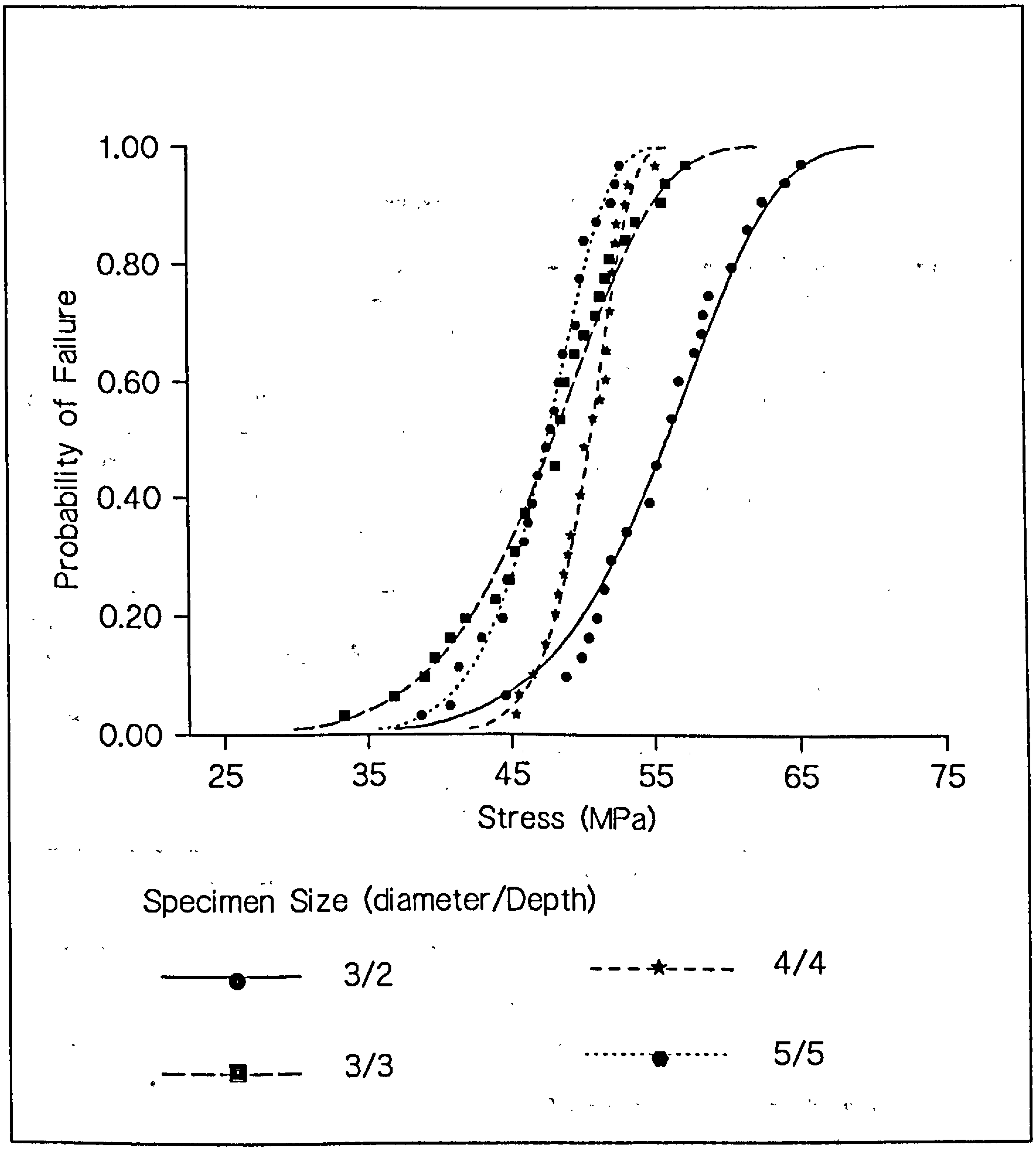


FIGURE 5.3.3.7
Diametral tensile strength of Occlusin-Probability of failure versus diametral tensile stress tested at crosshead speed 1mm/min for the specimens of various diameter/length ratios.
Specimens are bench dried for 7 days prior testing.

TABLE 5.3.3.8

Summary of Weibull analysis-Diametral tensile strength of Occlusin tested at crosshead speed 10mm/min for the specimens of various diameter/length ratios.

Diameter/Length Ratios	3:2	3:3	4:4	5:5
Weibull Modulus	9.3	9.4	15.4	14.0
Characteristic Strength+	55.8	48.9	50.3	50.1
Standard Error of Modulus	0.19	0.38	0.83	0.23
Coeff. of Correlation	0.99	0.96	0.93	0.99
Mean Strength+	53.1	46.5	48.7	48.3
Deviation Coefficient (%)	11.3	11.4	6.9	7.7
Stress+ at Failure Probability				
0.01% - Weibull	20.8	18.3	27.7	25.9
Normal	49.0	42.9	46.4	45.8
1% - Weibull	34.1	29.9	37.3	36.0
Student	50.5	44.2	47.3	46.7
99.99% - Weibull	65.8	57.6	55.6	55.8
Normal	57.2	50.1	51.0	50.8

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-Very highly significant difference between strength and specimen size (P<0.001).

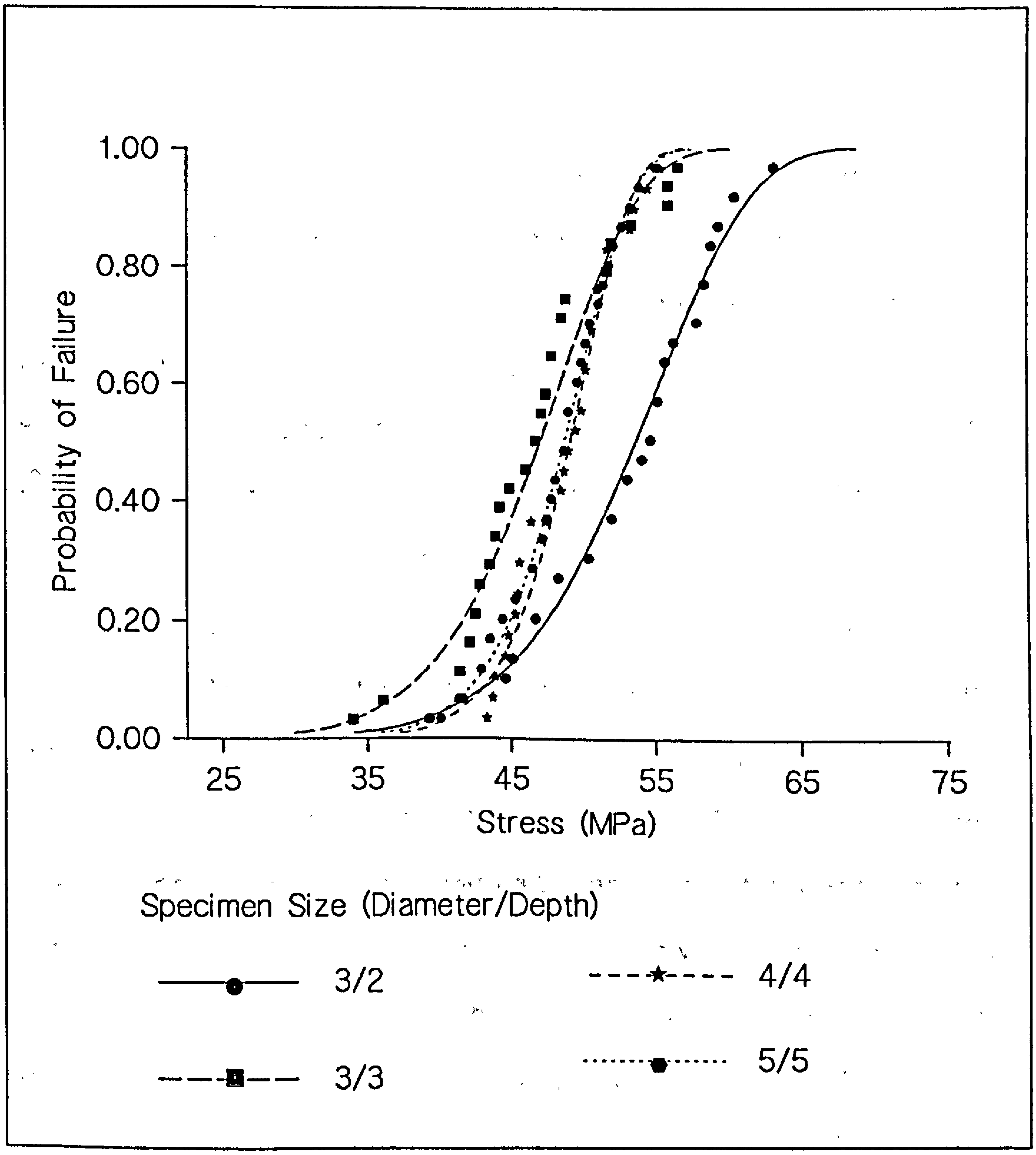


FIGURE 5.3.3.8
Diametral tensile strength of Occlusin-Probability of failure versus diametral tensile stress tested at crosshead speed 10mm/min for the specimens of various diameter/length ratios.
Specimens are bench dried for 7 days prior testing.

5.3.1 The Effect of Specimen Size and Crosshead Speed on The Diametral Tensile Strength of Plaster of Paris.

The specimens of 18 mm diameter by 10 mm, 15 mm, 20 mm and 25 mm length for the diametral tensile were coded as size 1, 2, 3 and 4, respectively. Each size had undergone a series of tests with crosshead speeds of 0.1, 0.5 1 and 10 mm per minute. Figures 5.3.1.1, 5.3.1.2, 5.3.1.3 and 5.3.1.4 show the results for the effect of specimen size on the diametral tensile strength of Plaster of Paris. Tables 5.3.1.1, 5.3.1.2, 5.3.1.3 and 5.3.1.4 show the summary of the 'strength analysis' for specimen sizes 1, 2, 3 and 4, respectively. Figures 5.3.1.5, 5.3.1.6, 5.3.1.7 and 5.3.1.8 are the graphs showing the results for the effect of crosshead speed on the diametral tensile strength of plaster of paris. The Weibull analysis summary is shown in Tables 5.3.1.5, 5.3.1.6, 5.3.1.7 and 5.3.1.8. It can be seen from Tables 5.3.1.1, 5.3.1.2, 5.3.1.3, 5.3.1.4, 5.3.1.5, 5.3.1.6, 5.3.1.7 and 5.3.1.8 that the correlation coefficients for all the tests are high. This means that the data collected from the diametral tensile tests show a good 'fit' to the Weibull Distribution equation.

Analysis of variance (ANOVA) showed that there was no significant difference between the mean diametral tensile strength for variation in specimen size ($P>0.05$). This indicates that there was no effect due to specimen size on the diametral tensile strength. However one-way analysis showed that there was a significant variation of the mean diametral tensile strength with specimen size when the tests were carried out at crosshead speed of 1 mm per minute ($p<0.05$). Table 5.3.1.2 shows the results for the tests carried out at crosshead speed of 1 mm per minute. There are two groups of mean strength reported. The mean diametral tensile strength of the specimens size 18 mm diameter by 10 mm length and the mean diametral tensile strength of the specimens size 18 mm diameter by 15 mm length are approximately the same. The Tukey range test shows that the mean diametral strengths of these specimen sizes are not significantly different at the 5 percent significance level. The Tukey range test also shows the mean strength of the specimen sizes 18 mm diameter by 20 mm length and 18 mm diameter by 25 mm length are not significantly different at the 5 percent significance level. This may suggest that there were two categories of diameter/length ratio present. Since the strain rate is constant, the other variable may be a diameter/length ratio. The diameter/length ratio for the specimen sizes 18 mm diameter by 10 mm length and 18 mm diameter by 15 mm length are approximately the same and the diameter/length ratio for the specimen sizes 18 mm diameter by 20 mm length and 18 mm diameter by 25 mm length are also approximately the same. This is may the reason why the mean diametral tensile strengths of these specimen sizes are approximately the same. These effects also shown by Weibull statistic that the characteristic strengths of the specimen sizes 18 mm diameter by 10 mm length and 18 mm diameter by 15 mm length are the same and the characteristic strengths of the test of the specimen sizes 18 mm diameter by 20 mm length and 18 mm diameter by 25 mm length are also the same. It has been discussed in chapter two that the specimen of diameter/length ratio of 1:1 is suitable for the diametral tensile test (Stanler and Wendt:1987, Price and Murray:1973, Williams:1967). The specimen sizes 18 mm diameter by 15 mm length and 18 mm diameter by 20 mm length may represent the specimens of diameter/length ratio of 1:1. It has been reported from this experiment that the strengths of the specimen sizes 18 mm diameter by 15 mm length and 15 mm diameter by 20 mm length were significantly different ($P<0.05$). It was observed at the time of testing that the mode of failure of diametral tensile of Plaster of Paris is catastrophic. A more catastrophic failure is observed at a higher crosshead speed. Catastrophic failure also varies with specimen size. This may be due to the size and quantity of flaws. The probability of more flaws being present in a larger specimen is higher than for a smaller specimen. The size of flaws in a larger specimen may also be larger than the size of flaws in a smaller specimens. This is shown clearly in Figure 5.3.1.3 that the diametral tensile strengths increase as the specimen size increases. From the explanation ~~explaination~~ above, it has been shown that the test carried out at a crosshead speed of 1 mm per minute did not produce reliable results. However it can be shown from the results of this experiment that the specimen size approximately equal to a diameter/length ratio of 1:1 may be a suitable specimen size for the diametral tensile test. The value of the Weibull modulus may reach an optimum value when specimens of a diameter/length ratio of 1:1 are tested. The test results of the specimens of diameter/length ratio of 1:1 were found more reliable as a low value of deviation coefficient was obtained. According to these results, the mean diametral tensile strength of Plaster of Paris varies with specimen size for the test carried out at a crosshead speed of 1 mm per minute. This does not mean that the specimen of size approximately equal to diameter/length ratio of 1:1 wont give a reliable result when tested with a crosshead speed 1 mm per minute. As has been demonstrated here, the specimen size 18 mm diameter by 15 mm length performed better than the other specimen sizes when tested at crosshead speed of 1 mm per minute. For the tests carried out at other crosshead speeds, there was no significant variation between the mean diametral tensile strength with specimen size. One-way analysis showed that there was no significant variation of the mean diametral tensile strength with specimen size for the tests carried out at crosshead speeds 10 mm per minute ($p>0.05$), 0.5 mm per minute ($p>0.05$) and 0.1 mm per minute ($p>0.05$). The test carried out at a crosshead speed of 0.5 mm per minute gave the highest probability ($p=0.66$). This shows that the crosshead speed

0.5 mm per minute may be the most reliable for the diametral tensile test.

Table 5.3.1.3 shows the results for the tests carried out at crosshead speed of 0.5 mm per minute. The Tukey range test showed that the mean strength of the specimen sizes 18 mm diameter by 15 mm length, 18 mm diameter by 20 mm length and 18 mm diameter by 25 mm length were not significantly different from each other at 5 percent significance level. This was because the deviation coefficient and mean strength of the specimen sizes 18 mm diameter by 15 mm length and 18 mm diameter by 20 mm length were approximately the same. The estimated stress by Normal statistic at all levels of failure probability were also the same. The estimated stress by Normal statistic at all levels of failure probability for the specimen size 18 mm diameter by 20 mm length and 18 mm diameter by 25 mm length were different. This was because their deviation coefficient were different, even though their mean strengths were the same. This result may given an explaination to why some brittle materials fail at a lower strength than other brittle materials, even though their mean strengths are the same. Table 5.3.1.3 also shows the results of the Weibull statistic for the various specimen sizes that were tested at a crosshead speed of 0.5 mm per minute. The Weibull modulus of the tests for the specimen sizes 18 mm diameter by 15 mm length and 18 mm diameter by 20 mm length were approximately the same. The values of their characteristic strength were also approximately the same. As the result it produced the same value of stress estimated at all levels of failure probability. This is clearly shown in Figure 5.3.1.3 where the curves of the specimen sizes 18 mm diameter by 15 mm length and 18 mm diameter by 20 mm length are close to each other. This may be because the specimen sizes were approximately equal to a diameter/length ratio of 1:1, particularly for the specimen size 18 mm diameter by 15 mm length and 18 mm diameter by 20 mm length. (As said to give reliable result for the diametral tensile test). And this is what happened when the specimens of diameter/length ratio of approximately 1:1 were tested with a crosshead speed of 0.5 mm per minute. Therefore a crosshead speed 0.5 mm per minute may be suitable for the diametral tensile test for Plaster of Paris.

Table 5.3.1.1 shows the results for the test carried out at a crosshead speed 10 mm per minute. In this test, the specimen sizes approximate to a diameter/length ratio of 1:1 which gives a better result. This is in agreement with the results of the tests that have been carried out at crosshead speeds of 1 and 0.5 mm per minute. The mean and characteristic strengths for the specimens of size 18 mm diameter by 10 mm length, 18 mm diameter by 20 mm length and 18 mm diameter by 25 mm length are the same but their deviation coefficients and Weibull moduli are different.

This may explain why the performance of the materials are different although their mean and characteristic strengths are approximately the same. It may be seen clearly from in 5.3.1.1 that the performances of the specimen sizes 18 mm diameter by 15 mm length and 18 mm diameter by 20 mm length, at lower probability of failure, are better than the performances of the other two specimen sizes. However the specimens of size 18 mm diameter by 15 mm length performed better than the other specimens sizes at all levels of failure probabilities. This may perhaps suggest that the specimen size 18 mm diameter by 15 mm length may be reasonably suitable for the diametral tensile test, because of the variation in Weibull modulus and coefficient deviation(%), a crosshead speed 10 mm per minute may not be suitable for the diametral tensile test.

Table 5.3.1.4 shows the results for the tests carried out at crosshead speed of 0.1 mm per minute. As before, the specimen sizes approximate to a diameter/length ratio of 1:1 to give the best results. The mean strengths of the tests of the specimen size 18 mm diameter by 15 mm length and 18 mm diameter by 20 mm length were the same, but their deviation coefficient are different. The same results are also shown by the Weibull statistic, that their characteristic strengths are the same but they have different Weibull moduli. As a result, the stresses estimated at any level of failure probability are different. The same results are shown graphically in Figure 5.3.1.4. The Weibull curves for all the specimen sizes are separated from each other due to the difference in the value of Weibull modulus. Therefore as explained in the previous paragraph, a crosshead speed of 0.1 mm per minute may not suitable for the diametral tensile test when compared to the crosshead speed of 0.5 mm per minute. This phenomenon may be due to the mode at failure. The failure of the specimen undergoing a diametral tensile test is observed to be catastrophic. Therefore a high strain rate applied to the specimen during testing may be more disastrous. This kind of failure may not depend on whether the specimen fails when the most critical flaw has been initiated or not. In addition it may not reflect the mode of failure of brittle materials. Failure in brittle materials is due to the flaws (McLean:1979), when the most critical flaw has being initiated a crack that may cause failure propagates from it. It is afraid that the test may not valid. Therefore this suggests that crosshead speed of 10 mm per minute may not be appropriate for the diametral tensile test. A test with a very low strain rate may also not be appropriate as the specimen may not fail when the most critical flaw has been initiated as a plastic flow occurs. This may not characterize the mode of failure for the brittle material. This means that a crosshead speed of 0.1 mm per minute may not be suitable for the diametral tensile test. Therefore crosshead speeds of 1 and 0.5 mm per minute may be considered.

Analysis of variance (ANOVA) showed that there was a significant difference between the mean diametral tensile strengths for varying crosshead speed ($P<0.001$). This is an early indication showing the effect of crosshead speed on the diametral tensile strength. One-way analysis showed that there was a significant difference between the mean diametral tensile strengths for varying crosshead speed when the test was carried out on the specimen sizes 18 mm diameter by 10 mm length ($p<0.05$) and 18 mm diameter by 25 mm length ($p<0.01$). However there is no significant difference between the mean diametral tensile strength and crosshead speed when the test is carried out for the specimen sizes 18 mm diameter by 15 mm length (One-way, $p>0.05$) and 18 mm diameter by 20 mm length (One-way, $p>0.05$). This means that the crosshead speed does not affect the diametral tensile strength of Plaster of Paris when the specimen sizes 18 mm diameter by 15 mm length and 18 mm diameter by 20 mm length were used. However the tests for the specimen size of 18 mm diameter by 15 mm length was more significant than 18 mm diameter by 20 mm length specimen size. This indicates that the specimen size of 18 mm diameter by 15 mm length may given more reliable results when compared to the test for the specimen size 18 mm diameter by 20 mm length. Therefore this is in agreement with the finding previously discussed where the specimen size 18 mm diameter by 15 mm length is suitable for use in the diametral tensile test.

As previously discussed, the tests that have been carried out at a crosshead speeds of 0.1 and 10 mm per minute have been considered not appropriate for the diametral tensile test. Therefore discussion may focus on the tests that have been carried out at a crosshead speed of 0.5 and 1 mm per minute. Table 5.3.1.6 shows the results for the specimens of size 18 mm diameter by 15 mm length that have been tested at various crosshead speeds. The Tukey range test showed the mean strength for the tests carried out at crosshead speeds 1 mm per minute and 0.5 mm per minute were not significantly different from each other. The deviation coefficient for the tests carried out at crosshead speeds 1 mm per minute and 0.5 mm per minute are approximately the same. This is also shown by Weibull statistic where the characteristic strength and Weibull modulus for the tests carried out at crosshead speeds 0.5 mm per minute and 1 mm per minute are approximately the same. As a result, the stresses estimated at any level of failure probability were approximately the same. This is can be seen in Figure 5.3.1.6 where the Weibull curve for the tests carried out at crosshead speeds 0.5 and 1 mm per minute are close to each other. As already noted in previous discussion, the specimen size approximately equal to diameter/length ratio of 1:1 gave better results when the specimens were tested at a crosshead speed of 0.5 mm per minute. And at other crosshead speeds, the specimen size 18 mm diameter by 15 mm length showed a better performance than other specimen sizes. Here those arguments have been found in agreement with the results of this studies.

Table 5.3.1.5 shows the results of the tests for the specimens of 18 mm diameter by 10 mm length that have been tested at various crosshead speeds. The Tukey range test showed that the mean strength for the tests carried out at crosshead speeds 10 mm per minute, 1 mm per minute and 0.5 mm per minute were not significantly different from each other at the 5 percent significance level. However their deviation coefficients are different from each other. The Weibull statistic shows that Weibull modulus and characteristic strength increase as crosshead speed increases from 0.5 mm per minute to 10 mm per minute. This is clearly shown in Figure 5.3.1.5 where all the Weibull curves are separately situated from each other. As a result, a specimen size 18 mm diameter by 10 mm length may not suitable for the diametral tensile test. This may be due to the 'thin' specimen size. In the discussion of the previous paragraph, it is observed that the mode of failure of diametral tensile test specimen is catastrophic. 'Thin' specimens may cause a more disastrous failure. This may not produce a reliable result as it has been shown in this experiment that the mean and characteristic strengths increase as crosshead speed increases. This is also shown by the variation in the value of Weibull modulus and coefficient deviation.

Table 5.3.1.7 shows the results of the tests for the specimens of 18 mm diameter by 20 mm length that have been tested at various crosshead speeds. The Tukey range test shows that the mean strengths for the tests carried out at a crosshead speeds of 0.5 mm per minute and 1 mm per minute are not significantly different at the 5 percent significance level. The deviation coefficients for the tests carried out at crosshead speeds 0.5 mm per minute and 1 mm per minute are also approximately the same. This is also shown by Weibull statistic. The characteristic strengths and Weibull moduli of the specimens that have been tested at crosshead speeds 0.5 mm per minute and 1 mm per minute are approximately the same. This effect is clearly shown in Figure 5.3.1.7 where the curves for these tests are close to each other. According to the Normal statistic, the specimen size 18 mm diameter by 20 mm length may be considered suitable for the diametral tensile test because the mean strength of the specimens tested at crosshead speeds 0.5 and 1 mm per minute are not significantly different at the 5 percent significance level (P)0.05). In addition, the performances of the specimens that have been tested at a crosshead speeds of 0.5 and 1 mm per minute are better than the performances of the specimens for the other tests. It has been said that the specimen size of approximately equal to diameter/length ratio of 2:1 gave a reliable result (Stanler and Wendt:1987, Price and Murray:1973, Williams:1967). However for the specimens of size 18 mm diameter by 20 mm length, a crosshead speed of 1 mm per minute is found to be more suitable for the diametral tensile test than a crosshead speed of 0.5 mm per minute. This is because the performances of the specimens when tested at a crosshead speed of 1 mm per minute are better than the performances of the same specimens that have been tested at a crosshead speed of 0.5 mm per minute.

Table 5.3.1.8 shows the results of the compressive tests for the specimen size 18 mm diameter by 25 mm length that have been tested at various crosshead speeds. The Tukey range test shows that the mean strengths for the tests carried out at crosshead speeds of 0.5 mm per minute and 1 mm per minute are not significantly different at the 5 percent significance level, but their deviation coefficients are different from each other. Weibull statistic shows that the characteristic strength of the specimens that have been tested at crosshead speeds of 0.5 mm per minute and 1 mm per minute are approximately the same but their value of Weibull modulus are different. This is clearly shown in Figure 5.3.1.8 where all the curves are separated from each other. As a result, a specimen size of 18 mm diameter by 25 mm length may not be suitable for the diametral tensile test of plaster of paris. The main reason why the Weibull and Normal parameters varied was that the diameter/length ratio of the specimen was less than 1:1. It has been said that a specimen size of approximately equal to diameter/length ratio of 2:1 gave a reliable result (Stanler and Wendt:1987, Price and Murray:1973, Williams:1967). In addition, the values of Weibull moduli for these tests are low when compared to the values Weibull moduli for the tests that have been carried out for the specimen sizes 18 mm diameter by 15 mm length and 18 mm diameter by 20 mm length. A low Weibull modulus may represent unreliable results. This is because of the scatter of the test data. As has been discussed earlier in this section, this may be due to the size and quantity of the flaws. In a larger specimen, the probability of more flaws being present is higher when compared to the smaller specimens. The probability of a larger size of flaws may also be greater in a large specimen.

The summary that can be put down from this test is that for Dental Plaster, a more statistically reliable result can be obtained by carrying out the diametral tensile test at a crosshead speed of 0.5 mm per minute. The specimen size of diameter/length ratio in the range 2:1 and 1:1 may give a reliable results.

5.3.2 The Effect of Specimen Size and Crosshead Speed on the Diametral Tensile Strength of Opalux.

The effect of crosshead speed on diametral tensile strength is shown in Tables 5.3.2.1, 5.3.2.2, 5.3.2.3 and 5.3.2.4 and Figures 5.3.2.1, 5.3.2.2, 5.3.2.3 and 5.3.2.4. The specimen sizes were 3 mm diameter by 2 mm length, 4 mm diameter by 3 mm length, 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length. For each specimen size, a crosshead speed of 0.1, 0.5, 1 and 10 mm per minute was used. There are two groups of specimens that can be seen from the specimen sizes, one with Diameter/Length ratios greater than 1 and the other equal to 1. Tables 5.3.2.5, 5.3.2.6, 5.3.2.7 and 5.3.2.8 and Figures 5.3.2.5, 5.3.2.6, 5.3.2.7 and 5.3.2.8 show the results for the effect of specimen size on diametral tensile strength. The data collected from the diametral tensile test of Opalux 'fits' the Weibull distribution as is shown by a high value for the correlation coefficient.

Oneway analysis showed that there was no significant difference (P>0.05) between the mean diametral tensile strengths for the various specimen sizes when the tests were carried out at all the crosshead speeds. However at a crosshead speed of 0.5 mm per minute, Oneway analysis gives the highest probability and the Weibull curves for this tests (Figure 5.3.2.6) are more close to each other when compared to the other tests. This is in agreement with the findings for the diametral tensile strength of Plaster of Paris, that a crosshead speed of 0.5 mm per minute should be used for the diametral tensile test.

Table 5.3.2.6 shows the results for the various specimen sizes tested at a crosshead speed of 0.5 mm per minute. The Tukey range test shows that the mean diametral tensile strengths of specimen groups are not significantly different from each other at the 5 percent significance level. However their deviation coefficients are different from each other, except for the specimen sizes 3 mm diameter by 2 mm length and 4 mm diameter by 4 mm length. Weibull statistic shows that the characteristic strength for all groups of specimen sizes are approximately the same. Weibull modulus for the specimen for the specimen sizes 3 mm diameter by 2 mm length and 4 mm diameter by 4 mm length are approximately the same. However the value of Weibull modulus for the specimen size 4 mm diameter by 3 mm length is the highest. This means that the data of this test are less scatter when compared to the data of the other tests. Therefore it shows that the specimen size 4 mm diameter by 3 mm length produces more reliable results. According to Figure 5.3.2.6, the performance at a lower failure probability is good for the specimen sizes 3 mm diameter by 2 mm length, 4 mm diameter by 3 mm length and 4 mm diameter by 4 mm length. However specimen size 4 mm diameter by 3 mm length gives a better performance than the other specimen sizes. According to the results shown in Table 5.3.2.6 and Figure 5.3.2.6, the specimen size 4 mm diameter by 3 mm length should be suitable for the diametral tensile test. The results in these investigation are in agreement with the findings for the diametral tensile strength of Plaster of Paris. It has been stated that a specimen with diameter/length ratios in the range 2:1 and 1:1 may give reliable results. This has also been confirmed by the findings of other workers where a specimen size of diameter/length ratio of 1:1 produced a reliable results (Stanler and Wendt:1987, Price and Murray:1973, Williams: 1967). However this is not the case for the specimen size 5 mm diameter by 5 mm length. The results of this test are unreliable because the Weibull modulus calculated is low when compared to the other Weibull moduli of the tests for the other specimen sizes. This indicates the degree of scatter of in the data and this may be due to the size and quantity of flaws in the specimen. The presence of flaws in light-activated composite resins have been reported by many workers (Reinhardt et al:1982, Gotfredsen, Horsted and Krugstrup: 1983, Dijken, Ruyter and Hollad:1986). As discussed previously these factors effect the strength of brittle materials. The brittleness of the material increases as the size and numbers of flaws increase. Furthermore the degree of polymerization may also have some effect on the strength of the polymeric materials. A poorly connecting network in a light-activated composite resin may be because of uncured dimethacrylate molecules and this may effect the strength of the polymeric materials (Asmussen:1982, Ruyther and Oysaed:1982, Ruyther and Svendsen:1978)

The results for the various specimen sizes that have been tested at a crosshead speed of 1 mm per minute are shown in Table 5.3.2.7 and Figure 5.3.2.7. The Tukey range test showed that there was no variation between the mean strength with specimen size at the 5 percent significance level except for the mean diametral tensile strength of the specimen size 3 mm diameter by 2 mm length. However their deviation coefficients are vary. Weibull statistic shows that the characteristic strengths for all the specimen sizes are approximately the same except for the characteristic diametral tensile strength of the specimen size 3 mm diameter by 2 mm length but their values of Weibull moduli vary. The test carried out with specimen size 3 mm diameter by 2 mm length give the highest characteristic strength and Weibull modulus. The performance of all specimen sizes are approximately the same except for the specimen size 3 mm diameter by 2 mm length. This is also shown clearly in Figure 5.3.2.7 , the Weibull curves for the specimen sizes 4 mm diameter by 3 mm length, 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are very close to each other at a lower failure probability. The performance of the test carried out with the specimen size 3 mm diameter by 2 mm length is slightly better than other specimen sizes. This may be due to a high degree of polymerisation. This is because the same exposure time was used to cure all the specimens. The volume of resin required for the specimen size 3 mm diameter by 2 mm length is less when compared to the volume of resin required for other specimen sizes. Therefore more polymer have been polymerised and a higher crosslink density of the polymer obtained and therefore a gain in strength (Braden and Causton:1973, Braden, Causton and Clarke:1976).. It has been discussed in chapter two, that the degree of polymerisation will also affect the strength of a resin. In addition, the size and number of flaws present in the specimen may also have some effect on the strength of polymeric materials. As previously discussed, the probability of more flaws being present in small specimens is less than the probability of more flaws being present in larger specimens. With respect to these results, the specimen size of diameter/length ratio in the range of 2:1 to 1:1 may be suitable for the diametral tensile test when the same degree of polymerisation is taken into consideration.

Table 5.3.2.8 shows the results for the diametral tensile tests for various specimen sizes that were tested at a crosshead speed 10 mm per minute. The Tukey range test shows that the mean strengths of all the specimen sizes are not significantly different from each other at the 5 percent significance level except for the specimen size 3 mm diameter by 2 mm length. The mean diametral tensile strength of the specimen size 3 mm diameter by 2 mm length is higher than that of the other specimen sizes. It has been explained in the paragraph above that this may be due to the degree of polymerisation. Although it has been shown by the Tukey range test that the mean diametral strengths of the specimen size 4 mm diameter by 3 mm length, 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are approximately the same, the deviation coefficients of the specimen sizes 4 mm diameter by 3 mm length is less than the deviation coefficient of the other specimen sizes. Thus the Weibull modulus of the specimen size 4 mm diameter by 3 mm length is higher when compared to the Weibull modulus of the other specimen sizes. The deviation coefficient of the specimen size 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are approximately the same. Therefore the value of Weibull modulus for the specimen size 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are also the same. This shows that the specimens of size 4 mm diameter and 3 mm length were less brittle when compared to the specimens of size 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length when the tests were carried out at a crosshead speed of 10 mm per minute. This may be due to a large number of flaws being present in the large specimens. That may explain why the strength of the specimen size 4 mm diameter by 4 mm length is greater than the strength of the specimen size 5 mm diameter by 5 mm length. The degree of polymerization may also have some effect. It has been discussed previously, that uncured polymer molecules may caused a weak network in the composite resin thus lowering its strength. Further more, the performance of the specimen size 4 mm diameter by 3 mm length is better than the performances of the specimen sizes 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length which are approximately the same. In this test it shows the reliability of the specimen size 4 mm diameter by 3 mm length. Therefore from this investigation, when the various specimen sizes have been tested at a crosshead speed of 10 mm per minute, it shows that there is a difference in the diametral tensile strength between the specimens of diameter/length ratio in the range 2:1 and 1:1. It has been discussed for the diametral tensile test of Plaster of Paris that the test carried out at crosshead speed 10 mm per minute may not suitable for diametral tensile test of Opalux.

Table 5.3.2.5 and Figure 5.3.2.5 show the results of the diametral tensile test of Opalux where various specimen sizes have been tested at a crosshead speed of 0.1 mm per minute. The Tukey range test shows that the mean strengths of the specimen sizes 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are approximately the same. However their deviation coefficients are different. This behaviour is the same as that which has been discussed in the above paragraph. The mean diametral tensile strength of the specimen size 3 mm diameter by 2 mm length is the highest when compared to the mean diametral tensile strength of the other specimen sizes. This may be due to the degree of polymerisation. This has also discussed in the above paragraph. The Weibull statistic shows that the characteristic strength and Weibull modulus for the specimen sizes 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are approximately the same. However the Weibull modulus for the specimen size 4 mm diameter by 3 mm length is less than that for the other tests. This indicate that the data of the test may give reliable results. Figure 5.3.2.5 shows graphically the effect of specimen size on the diametral tensile strength of Opalux. This can be seen in Figure 5.3.2.5 where the Weibull curves for specimen sizes 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are close to each other. The performances of these two tests are approximately the same. However the performance of the specimen size 4 mm diameter by 3 mm length is much better than those other specimen sizes. It has been discussed, for the diametral tensile test of Plaster of Paris, that the test carried out at a crosshead speed 0.1 mm per minute may be invalid for the diametral tensile test. However in this test it ~~domostrates~~ demonstrates the reliability of the specimen size 4 mm diameter by 3 mm length as an optimum specimen size that gave reliable results.

The results for the effect of crosshead speed on the diametral tensile strength are shown in Tables 5.3.2.1, 5.3.2.2, 5.3.2.3 and 5.3.2.4 and Figures 5.3.2.1, 5.3.2.2, 5.3.2.3 and 5.3.2.4 . For the specimens of diameter/length ratio greater than 1 (i.e for the specimen size 3 mm diameter by 2 mm length and 4 mm diameter by 3 mm length), One-way analysis of variance shows that, for specimens of diameter/length ratio 3:2 (Table 5.3.2.1), there is no significant difference (P>0.05) between the mean diametral tensile strength of the specimens that have been tested at the various crosshead speeds. However there is a significant difference between the mean diametral tensile strengths of the specimen size 4 mm diameter by 3 mm length (P<0.05) with changing crosshead speed. The Tukey range test shows that the mean strengths of the tests carried out at crosshead speeds of 0.5 mm per minute, 1 mm per minute and 10 mm per minute are not significantly different from each other at the 5 percent significance level. The diametral tensile strength of the specimens of 4 mm diameter by 3 mm length when tested at a crosshead speed of 0.1 mm per minute is less than the diametral tensile strength of the specimens for the other tests. The characteristic strength for the tests carried out at crosshead speeds 0.5 mm per minute, 1 mm per minute and 10 mm per minute are approximately the same. Figure 5.3.2.2 shows the graphical representation of the Weibull statistic. The curve for the tests carried out at crosshead speeds of 1 mm per minute and 10 mm per minute are close to each other. This is because their Weibull modulus and characteristic strength are approximately the same. The gradient of the straight line of the curve for the test carried out at crosshead speed 0.1 mm per minute is greater than those of the other test. This is because the value of Weibull modulus of the test carried out at crosshead speed 0.1 mm per minute is higher than other tests. There the specimens that were tested at a crosshead speed of 0.1 mm per minute were less brittle than the specimens that were tested at other crosshead speeds. The Weibull modulus for the tests carried out at crosshead speeds of 1 mm per minute and 10 mm per minute are approximately the same. But the Weibull moduli for these groups of test is less than the value of Weibull modulus for the test carried out at a crosshead speed of 0.5 mm per minute. That is probably why the performance of the specimens that have been tested at a crosshead speed of 0.5 mm per minute was better than the performance of the specimens that were tested at other crosshead speeds. The performance of the specimens that were tested at crosshead speed of 0.5 mm per minute is also illustrated in Figure 5.3.2.2 . where at a lower probability of failure, the specimens that have been tested gave a higher strength. Thus from the discussion above, a crosshead speed of 0.5 mm per minute may be used for the diametral tensile test as it produced reliable results with the specimen size 4 mm diameter by 3 mm length.

The failure of a specimen undergoing a diametral tensile test is instant failure i.e catastrophic (Darvell:1990). Thus a very low strain rate may not be appropriate because the failure may not be instantaneous when the most critical flaw has been initiated. Local elastic and plastic deformation may be developed before failure (Darvell:1990) and this may be responsible for lowering the diametral tensile strength of Opalux. The development of local elastic and plastic deformation may be due to the low crosslink density of the polymer. The crosslink density is dependent on the degree of polymerization. Some dimethacrylate molecules in the polymer remain unreacted (Ruyther and Svendsen:1978, Asmussen:1982, Ruyther and Oysaed:1982) and these may lead to weak network in the system. When these specimens have been stored in distilled water for 7 days, some of the partially cured polymer may be degraded by water (Braden and Causton:1973, Braden, Causton and Clarke:1976). This may produced a weak spot in the specimen. This means that crosshead speed of 0.1 mm per minute may not be suitable for the diametral tensile test. On the other hand, at a crosshead speed of 10 mm per minute, a high strain rate is applied to the specimen during testing making the mode of failure more disastrous. This is shown by a lower value of Weibull modulus for the specimens that have been tested at a crosshead speed of 10 mm per minute. The result of this test is not reliable as a low value of Weibull modulus indicates a wide scatter of data. As a result the performance of the specimens is not a good as the performances of the specimens tested at other crosshead speeds, even though it's mean strength is higher than the others. Thus this suggests that a crosshead speed of 10 mm per minute may not be appropriate for the diametral tensile test. In addition, this kind of failure may not depend on whether the specimen fails when the most critical flaw has been initiated or not. Therefore crosshead speeds of 0.5 and 1 mm per minute may be suitable for the diametral tensile test. However Table 5.3.2.2 shows the value of Weibull modulus of the specimens tested at a crosshead speed of 1 mm per minute is low when compared to the value of the Weibull modulus for the specimens tested at a crosshead speed of 0.5 mm per minute. The performance of the specimens tested at a crosshead speed of 0.5 mm per minute better than the performance of the specimen tested at a crosshead speed of 1 mm per minute, eventhough the mean strength of both specimens is the same. Thus it may be suggested that a specimen size 4 mm diameter by 3 mm length is the optimum diametral tensile specimen size. It may give the most reliable results when the specimens are tested at a crosshead speed of 0.5 mm per minute.

The mean strengths of the specimens of size 3 mm diameter by 2 mm length that have been tested at all crosshead speeds is approximately the same. This may be because of the degree of polymerisation. Because the same length of exposure has been used for both specimen sizes, the degree of polymerisation in specimens of size 3 mm diameter by 2 mm length may be greater than the degree of polymerisation in specimens of size 4 mm diameter by 3 mm length because less polymer molecules need to be polymerised for the specimens of size 3 mm diameter by 2 mm length. Polymerisation in the specimens of size 3 mm diameter by 2 mm length may be complete. Higher crosslink density may be present in the polymer and a result water absorption may be kept to minimum (Braden and Causton:1973, Braden, Causton and Clarke:1976). Table 5.3.2.1 shows the results of the diametral tensile tests of Opalux for the specimens of size 3 mm diameter by 2 mm length that have been tested at various crosshead speeds. The characteristic strength for the tests carried out at a crosshead speeds 0.1 mm per minute and 0.5 mm per minute are approximately the same. The Weibull modulus for the tests carried out at crosshead speeds of 0.1 mm per minute and 0.5 mm per minute are also approximately the same. This shows that the results of the test carried out at a crosshead speed of 0.1 mm per minute are as reliable as the results of the test carried out at a crosshead speed of 0.5 mm per minute. The characteristic strength for the tests carried out at a crosshead speeds 1 mm per minute and 10 mm per minute are approximately the same but the Weibull modulus for the tests carried out at crosshead speeds 1 mm per minute and 10 mm per minute are different. This means that the data of the specimens tested at a crosshead speed of 1 mm per minute has less scatter than the data of the specimens tested at a crosshead speed of 10 mm per minute. This shows that the mode of failure when the test that is carried out at a crosshead speed 10 mm per minute more is more catastrophic than the mode of failure for the test carried out at a crosshead speed 1 mm per minute. The mode of failure for the test that is carried out at a crosshead speed 10 mm per minute may be considered as over catastrophic and may not be suitable for the diametral tensile test. This is supported by a poor correlation coefficient for the specimens that have been tested at a crosshead speed of 10 mm per minute (Table 5.3.2.1). The performance at a lower probability of failure for the specimens that have been tested at a crosshead speed of 1 mm per minute is better than the performances of the specimens for the other tests. According to the results above, a crosshead speed of 1 mm per minute may be suitable for the diametral tensile test when a specimens of size 3 mm diameter by 2 mm length are used in the testing.

The above paragraphs showed the reliability of the specimens of diameter/length ratio greater than 1. At a crosshead speed 0.5 and 1 mm per minute, the specimen size 3 mm diameter by 2 mm length and 4 mm diameter by 3 mm length, respectively gave reliable results. For the specimen size of diameter/length ratio equal to 1, one-way analysis of variance shows that there is also no significant difference between the mean strength for the tests carried out at various crosshead for both 4 mm diameter by 4 mm length ($p=0.29$) and 5 mm diameter by 5 mm length ($p=0.05$). Tukey range tests for both specimen sizes, 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length, show that the mean diametral tensile strengths of the specimens tested at all crosshead speeds are not significantly different at the 0.05 significance level. This is clearly shown in Tables 5.3.2.3 and 5.3.2.4 . Both Tables show that the characteristic strength of the specimens tested at crosshead speeds of 0.5, 1 and 10 mm per minute are approximately the same. However the Weibull moduli are different. This effect can be seen graphically in Figure 5.3.2.3 and Figure 5.3.2.4 where the curves for the tests carried out at crosshead speeds 0.5, 1 and 10 mm per minute are randomly positioned. However these curves are close to each other and this means that the strengths are approximately the same. The curve for the specimens that have been tested at a crosshead speed of 0.1 mm per minute is separated from the group of the other curves as the strength is lower than that the others. This is shown for both specimen sizes. It may occur because some of the polymer in the specimens may be partially cured. As has been explained previously, local elastic and plastic deformation may result due to the unreacted monomer. This behaviour may lower the strength when the specimens are tested at a low crosshead speed. The specimens may also became less brittle when a low crosshead speed is used as it was observed that the Weibull modulus for the specimens that had been tested at a crosshead speed of 0.1 mm per minute was higher than that for the specimens of the other tests. The discussion above shows the reliability of the specimen size of diameter/length ratio of equal to 1. At a crosshead speed 0.5, 1 and 10 mm per minute, the specimen size 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length gave a reliable results.

The results of this investigation showed that for the specimen size of diameter/length ratio of greater than 1 (i.e for the specimen size 3 mm diameter by 2 mm length and 4 mm diameter by 3 mm length) a crosshead speed of 10 mm per minute is not suitable for the diametral tensile test. While for the specimen size of diameter/length ratio equal to than 1 (i.e for the specimen size 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length) a crosshead speed of 0.1 mm per minute is not suitable for the diametral tensile test. Therefore a general conclusion that can be drawn from this is, a crosshead speed of 0.5 mm per minute and 1 mm per minute may be suitable for the diametral tensile test of Opalux. A reliable results were obtained when the specimen size of diameter/length ratio ranging from 1 to 2 were used.

5.3.3 The Effect of Specimen Size and Crosshead Speed on The Diametral Tensile Strength of Occlusin.

The results for the effect of crosshead speed on the diametral tensile strength of Occlusin for a specimen size 3 mm diameter by 2 mm length are shown in Table 5.3.3.1 and Figure 5.3.3.1. The result for the specimens of Diameter/Length ratio of 1:1 are shown in Tables 5.3.3.2, 5.3.3.3, and 5.3.3.4 and Figures 5.3.3.2, 5.3.3.3, and 5.3.3.4 . The specimen sizes of 3 mm diameter by 3 mm length, 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length were tested with crosshead speeds of 0.1, 0.5, 1 and 10 mm per minute. Tables 5.3.3.5, 5.3.3.6, 5.3.3.7, and 5.3.3.8 and Figures 5.3.3.5, 5.3.3.6, 5.3.3.7, and 5.3.3.8 show the results for the effect of specimen size on the diametral tensile strength of Occlusin.

One-way analysis of variance for the effect of specimen size on diametral tensile strength of Occlusin shows that there is a very highly significant difference ($P<0.001$) between the mean diametral tensile strengths for the specimen sizes at all the crosshead speeds under evaluation. This shows that the specimen size does affect the diametral tensile strength of Occlusin. The results are shown in Tables 5.3.3.5, 5.3.3.6, 5.3.3.7 and 5.3.3.8 and Figures 5.3.3.5, 5.3.3.6, 5.3.3.7 and 5.3.3.8 .

Table 5.3.3.5 shows the results of the diametral tensile tests for various specimen sizes that have been tested at a crosshead speed of 0.1 mm per minute. The characteristic strength of all the specimen sizes are varies. It has been shown by the Tukey range test that the mean strengths of these specimen sizes are significantly different at the 5 percent significance level. In addition, it is observed that the Weibull moduli are also different. The Weibull modulus decreases as the specimen become larger. The value of Weibull modulus for the specimen size 3 mm diameter by 3 mm length is doubtful because it seems that the data did not well 'fit' the Weibull distribution. This is shown by a poor correlation coefficient. However from the remaining result, it may be assumed that the brittleness of the material varied with specimen size. The reason for this behaviour may be due to the size and number of flaws present in the specimens. In a large specimens, the probability of more flaws being present is high when compared to the small specimens. The size of flaws in a larger specimens may also be large. Specimen may become more brittle as the number of flaws in the specimen increases. The other reason may be due to the different degrees of polymerization. In a low degree of polymerization, unreacted polymer molecules may cause a poorly connected network. This may result in reducing the strength of a polymeric material (Ruyther and Oysaed:1982, Asmussen:1982, Ruyther and Svendsen:1978). It has been shown in Table 5.3.3.5 that the mean strength decreases as specimen size increases. Furthermore more local elastic and plastic deformation may be developed in poorly polymerised specimens. These specimens may be deteriorated by immersion in water, as composite resin may absorb water and undergo a hydroscopic expansion (Asmussen and Jorgensen:1972, Bowen et al:1982). At a low strain rate, the specimen may not fail immediately after the most critical flaw has been initiated. This may be because the mode of failure has been effected by the plastic deformation. Figure 5.3.3.5 shows the graphical version of the Weibull statistic. The graph shows that the Weibull curves for all the specimen sizes are separate from each other showing the differences in strength. This also shows that the specimen size affects the diametral tensile strength of Occlusin when the test is carried out at a crosshead speed 0.1 mm per minute.

Table 5.3.3.6 shows the results of the diametral tensile tests for various specimen sizes that have been tested at a crosshead speed of 0.5 mm per minute. There is a very highly significant difference between the characteristic strengths for varying specimen size. The Tukey range test shows the mean strength of the tests for the specimen sizes 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are approximately the same at the 5 percent significance level. The characteristic strengths of these specimen sizes are less than the characteristic strength for the specimen size 3 mm diameter by 2 mm length. The probability of flaws present in this specimen size is less than the probability of flaws present in a larger specimen. In addition the degree of polymerization in the specimen size 3 mm diameter by 2 mm length is higher than the degree of polymerization in a larger specimen, as has been discussed previously. Therefore the strength of the specimens of size 3mm diameter by 2 mm length is expected to be higher. In addition, the specimens may be more brittle as the mode at failure is not influenced by the plastic deformation. As has been shown the strength of the specimen size 3 mm diameter by 2 mm length is greater than the strength of the specimen sizes 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length and the Weibull modulus of the test for specimen size 3 mm diameter by 2 mm length is lower than the value of Weibull modulus for the specimen sizes 4 mm diameter by 4 mm and 5 mm diameter by 5 mm length. However from the results of the test for the specimen size 3 mm diameter by 2 mm length are doubtful as the correlation coefficient is poor. Figure 5.3.3.6 shows the graphical results of the Weibull statistic. The graph shows that the Weibull curves for the tests for the specimen sizes 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are close to each other showing their Weibull modulus and characteristic strength are the same. The performance at 0.01 percent failure probability of the tests for the specimen sizes 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length is better than the performance of the test for the specimen size 3 mm diameter by 2 mm length. At a failure probability greater than 1 percent, the performance of the test for the specimen size 3 mm diameter by 2 mm length is found to be much better than the performance of the tests for the specimen sizes 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length. However the correlation coefficient of the test for the specimen size 3 mm diameter by 2 mm length is very low. This indicates that the data of the test for the specimens of size 3 mm diameter by 2 mm length does not fit well to the Weibull distribution equation when the test is carried out at crosshead speed 0.5 mm per minute. Therefore the results for the specimen size 3 mm diameter by 2 mm length are doubtful. As a result, a specimen size of diameter/length ratio of 1:1 may be suitable for the diametral tensile test of Occlusin when the specimens are tested at a crosshead speed of 0.5 mm per minute.

Table 5.3.3.7 shows the results of the diametral tensile tests for various specimen sizes that have been tested at crosshead speed 1 mm per minute. There is a very highly significant difference between the mean strengths for varying specimen size. The Tukey range test shows that the mean strength of the specimen sizes 3 mm diameter by 3 mm length, 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are approximately the same at the 5 percent significance level. The mean strength of the specimen size 3 mm diameter by 2 mm length is the highest. As previously discussed this may be due to the degree of polymerisation. Plastic behaviour may not have influenced the mode of failure. Further more, the failure of a 'thin' specimen is very catastrophic when tested at a high crosshead speeds. That may be the reason why the mean strength of the specimen size 3 mm diameter by 2 mm length is significantly different from the mean strength of the other specimen sizes. Weibull statistic also shows, the characteristic strength of specimen size 3 mm diameter by 2 mm length is different when compared with the characteristic strength of the other specimen sizes (i.e 3 mm diameter by 3 mm length, 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length). The performance at lower probabilities of failure of the specimen size 3 mm diameter by 3 mm length, 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are different although the characteristic strengths are approximately the same. The performance of the specimen size 4 mm diameter by 4 mm length is better than the performance of the other specimen sizes. This may be because the specimen size 4 mm diameter by 4 mm length has a higher characteristic strength. The results of this experiments show that the specimens of diameter/length ratio of 1:1 may be suitable for the diametral tensile test, based on Normal statistic, because it has been shown by Tukey range test that the mean strength of the specimens of diameter/length ratio of 1:1 are not significantly different. This is also shown by Weibull statistic, where the characteristic strengths of these specimens are approximately the same. In addition Weibull statistic shows specimen size 4 mm diameter by 4 mm length is the most suitable for the diametral tensile test. This is because the performance of this specimen is better than other specimen sizes of the same diameter/length ratio of 1:1. Therefore specimen size 4 mm diameter by 4 mm length may give the most reliable results when a crosshead speed of 1 mm per minute is used to test the specimen.

Table 5.3.3.8 shows the results of the diametral tensile tests for various specimen sizes that have been tested at a crosshead speed 10 mm per minute. There is a very highly significant difference between the mean strengths for varying specimen size (one-way, $p<0.001$). However The Tukey range test shows that the mean strengths of the specimen sizes 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are approximately the same at the 5 percent significance level. The characteristic strengths of these specimen sizes are also approximately the same. It is observed from the Table 5.3.3.8 that the characteristic strength of the specimen size 3 mm diameter by 2 mm length is the highest but as previously discussed in this chapter, the failure of 'thin' specimens is very catastrophic when tested at a high crosshead speed. That may be the reason why the mean strength of the specimen size 3 mm diameter by 2 mm length is significantly different from the mean strength of the other specimen sizes. The performances of these specimen sizes can be seen clearly in Figure 5.3.3.8. The performance of the specimen size 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are better than the performance of the ~~the~~ other specimen sizes. This may be because these specimen sizes have a higher characteristic strength. The results of this experiment show that the specimens of diameter/length ratio of 1:1 may be suitable for the diametral tensile test. Based on Normal statistic, it has been shown by Tukey range test that the mean strength of the specimens of diameter/length ratio of 1:1 are not significantly different. This is also shown by Weibull statisic, where the characteristic strengths of these specimens are approximately the same. In addition Weibull statistic shows specimen size 4 mm diameter by 4 mm length and 5 mm diameter by 5 mm length are the most suitable for the diametral tensile test. This is because the performances of these specimens are better than other specimen sizes of the same diameter/length ratio of 1:1. Therefore specimen size 4 mm diameter by 4 mm length may give the most reliable results when a crosshead speed of 10 mm per minute is used to test the specimen.

One-way analysis of variance for the effect of crosshead speed on the diametral tensile strength of Occlusin shows that there is no significant difference (P>0.05) between the mean diametral tensile strengths for the specimens at various crosshead speeds, except for the specimen size 5 mm diameter by 5 mm length. The results of the diametral tensile strength test of Occlusin for a specimen size 3 mm diameter by 2 mm length are shown in Table 5.3.3.1 and Figure 5.3.3.1. The Tukey range test showed that there was no significant difference between the mean diametral tensile strengths ($p>0.05$). It can be seen in Table 5.3.3.1, that the mean and characteristic diametral tensile strengths for all the crosshead speeds are approximately the same. The deviation coefficient and Weibull modulus for the test carried out at crosshead speed 0.1 mm per minute were less than the deviation coefficient and Weibull modulus of the other tests. The deviation coefficient and Weibull modulus for the tests carried out at crosshead speeds 0.5, 1 and 10 mm per minute were approximately the same. This behaviour has been discussed previously in this chapter, i.e that the polymerisation in the specimens of size 3 mm diameter by 2 mm length may be completed. The mode of failure at a low crosshead speed may still be influenced by the plastic behaviour. This may be due to a low strain rate of testing. However the mode of failure is may not be influenced by the plastic behaviour as catastrophic failure is observed for the other crosshead speeds as crosshead speed increases. This may explain why the mean diametral tensile strength of the specimens that have been tested at a crosshead speed of 0.1 mm per minute is different from the mean diametral tensile strength of the other specimens that have been tested at a crosshead speed of 0.5, 1, and 10 mm per minute.

This effect is shown graphically in Figure 5.3.3.1. It can be seen from the graph that the Weibull curves for the tests carried out at a crosshead speed 0.5,1 and 10 mm per minute are close to each other. The curves for the test at crosshead 0.5 mm per minute is however slightly separated from the curves of the other tests. It has been said the results this test are doubtful as supported by a poor ~~corelation~~ correlation coefficient. Figure 5.3.3.1 also shows that the gradient of the straight part of the curve for the tests carried out at a crosshead speeds of 1 and 10 mm per minute are approximately the same. This may represent the same value of Weibull modulus. It can be seen from the graph that the performance at a lower failure probability for the tests carried out at a crosshead speeds of 1 and 10 mm per minute are approximately the same. According to the discussion above, specimen size 3 mm diameter by 2 mm length may not be suitable for the diametral tensile test of Occlusin when the specimens are tested at a crosshead speed of 0.1 mm per minute and 0.5 mm per minute.

Oneway analysis of variance showed there was no significant difference between the diametral tensile strengths for varying crosshead speed for the specimen size 3 mm diameter by 3 mm length (P>0.05). The Tukey range test for the specimens 3 mm diameter by 3 mm length (Table 5.3.3.2) showed that the mean diametral tensile strengths for each crosshead speed were not significantly different (P>0.05).

However it can be seen from Figure 5.3.3.2 that the Weibull curve for the test carried out at a crosshead speed of 0.1 mm per minute is slightly separated from the other curves. This shows the advantage of Weibull statistic over Normal statistic. The variation between the mean diametral tensile strength of the specimens that have been tested at a crosshead speed of 0.1 mm per minute with the mean strength specimens of the other tests may be due to the phenomenon that has been already discussed for the specimen size 3 mm diameter by 2 mm length. The value of Weibull modulus for the tests carried out at a crosshead speeds 1 mm per minute and 10 mm per minute are approximately the same. The value of Weibull modulus for the tests carried out at a crosshead speed of 0.5 mm per minute is slightly greater than the Weibull modulus for the other tests. This means that the specimens become more brittle with an increase in a crosshead speed. This is because the mode of failure becomes more catastrophic as crosshead speed increases. Figure 5.3.3.2 may show the performance of the specimens more clearly. Although the diametral tensile strength of the specimens that have been tested at a crosshead speeds of 0.5, 1 and 10 mm per minute are approximately the same, the performance of the specimens that have been tested at a crosshead speed of 0.5 mm per minute is better than the performances for the other tests.

Oneway analysis of variance showed there was no significant difference between the diametral tensile strengths for varying crosshead speed for the specimen size 4 mm diameter by 4 mm length (P>0.05). It can be seen that for the specimen size 4 mm diameter by 4 mm length (Table 5.3.3.3), the mean diametral tensile strength from all the groups are approximately the same. The Tukey range test shows that the mean diametral tensile strengths of the groups were not significantly different from each other at the 0.05 significance level. The deviation coefficient increases as the crosshead speed decreases from 0.1 mm per minute to 1 mm per minute and increases when the crosshead speed reached 10 mm per minute. This is also shown by the value of Weibull modulus. The value of Weibull modulus increases as the crosshead speed increases from 0.1 mm per minute to 1 mm per minute and decreases when the crosshead speed reached 10 mm per minute. However the results of the specimens that have been tested at a crosshead speed of 10 mm per minute are doubtful. This is because the data did not 'fit' the Weibull distribution as shown by a poor correlation coefficient. Therefore the specimens become less brittle with an increase in crosshead speed and the results become unreliable as crosshead speed increases. This is seen to be different from the results for the specimen size 3 mm diameter by 3 mm length. The reason for this may be due to the degree of polymerisation. The degree of polymerisation for the specimens of size 3 mm diameter by 3 mm length is higher than for the specimens of size 4 mm diameter by 4 mm length. Polymerisation in the specimens of size 4 mm diameter by 4 mm length may be incomplete. Partially cured polymer may produce a weak spot in the specimen. At lower crosshead speeds, specimens may fail due to the plastic behaviour while at a high crosshead speed, catastrophic failure may occur and this is dependent on the size and number of flaws in the specimen. Catastrophic failure shows a brittle behaviour. That is why the brittleness of the specimens increase as crosshead speed increases. Table 5.3.3.3 shows the estimated stress at all levels of failure probability for the test carried out at crosshead speed 1 mm per minute is higher than the stress estimated for the other tests. According to the Normal statistic, high mean strength and a lower value of deviation coefficient are the major factors responsible for this high estimated stress at all levels of failure probability. According to Weibull statistic, high Weibull modulus and high characteristic strength are the major factors responsible for this high estimated stress at all levels of failure probability. Thus in this case the performance of the test carried out at crosshead speed 1 mm per minute is better than other tests. With respect to these results, a crosshead speed of 1 mm per minute may be used for the diametral tensile test, if specimens of 4 mm diameter by 4 mm length are used.

Oneway analysis of variance showed there was a very significant difference ($P<0.001$) between the diametral tensile strengths for varying crosshead speed for the specimen size 5 mm diameter by 5 mm length (Table 5.3.3.4). The Tukey range test shows the mean strength for the tests carried out at crosshead speeds 0.5 mm per minute, 1 mm per minute and 10 mm per minute are not significantly different ($P>0.05$). The variation between the mean diametral tensile strength of the specimens that have been tested at a crosshead speed of 0.1 mm per minutes and the mean strength of specimen of the other tests may be due to the plastic behaviour that has been already discussed. This effect is also shown by the Weibull statistic. Weibull statistic shows that the characteristic strengths of the tests carried out at crosshead speeds 0.5, 1 and 10 mm per minute are approximately the same. However the value of the Weibull modulus varies. The Weibull modulus for the test carried out at crosshead 0.5 mm per minute is the highest. Thus this may be the reason why the performance of the test carried out at a crosshead speed of 0.5 mm per minute is better than the performance of the other tests. This is shown graphically in Figure 5.3.3.4. The Weibull curves for the tests carried out at crosshead speeds 0.5 mm per minute, 1 mm per minute and 10 mm per minute are approximately close to each other. This is because their Weibull moduli and characteristic strengths are approximately the same. At a lower probability of failure, the performance of those tests are approximately the same. However the performance of the test carried out at crosshead speed 0.5 mm per minute is found to be better than others. From the results of this experiment, it can be concluded that a crosshead speed of 0.5, 1 and 10 mm per minute may be used for the diametral tensile test when a specimen of size 5 mm diameter by 5 mm length is tested. However a crosshead speed of 0.5 mm per minute is thought to be more reliable because of the performance of the specimens tested with this crosshead speed is better than the other tests.

5.4 Summary and Conclusion

The results of this studied may be summarised as follows, a specimen size for the diametral tensile test should be of diameter/length ratio between 1:1 and 2:1. A specimen size of diameter/length ratio of 1:1 had been found to give a reliable results (Stanler and Wendt:1987, Price and Murray:1973, Williams:1967). This is partly in agreement with the findings that have been discussed. With this specimen size, it is found that a crosshead speed of 0.5, 1 and 10 mm per minute is suitable for use in the diametral tensile test. For a more brittle material, a crosshead speed of 10 mm per minute may not suitable. This is ~~demostrated~~ demonstrated by the diametral tensile test of Plaster of Paris. However a crosshead speed of 0.5 mm per minute is found to be the optimum crosshead speed for the diametral tensile test. This is because it performance was better than other crosshead speeds. A specimen size of 4 mm diameter by 3 mm length or 4 mm diameter by 4 mm length is the optimum specimen size for the diametral tensile test of Composite resin when a crosshead speed of 0.5 mm per minute was used. For the diametral tensile test of Plaster of Paris, a specimen size 18 mm diameter by 15 mm length gave the optimum results with the crosshead speed of 0.5 mm per minute.

The conclusion that can be drawn from the discussion is that a specimen size of diameter/length ratio between 2:1 and 1:1 may be used in the diametral tensile test. A crosshead speed of 0.5 or 1 mm per minute may be suitable for the diametral tensile test. Specimen sizes 4 mm diameter by 3 mm length and 4 mm diameter by 4 mm length are found to give reliable results when the specimens are tested with a crosshead speed of 0.5 or 1 mm per minute. However the specimen size 4 mm diameter by 3 mm length is the optimum size for a specimen that will give the most reliable results when a crosshead speed 0.5 mm per minute is used.

CHAPTER SIX

FLEXURAL TEST

6.1 The Determination of The Optimum Specimen Size And Crosshead Speed For The Flexural Test.

This part of the investigation was conducted to evaluate the effect of certain test parameters on the Flexural strength of Occlusin. Namely :-

(a) the effect of crosshead speed on the flexural strength.

(b) the effect of specimen size on the flexural strength.

These investigations were conducted firstly, to study the effect of crosshead speed on the flexural strength of Occlusin. The optimum crosshead speed for the flexural test would be determined and this speed would be used in further investigations to determine the flexural strength parameters of dental restorative materials. Secondly, the effect of the specimen size on the flexural strength of Occlusin was investigated. The optimum specimen size would be determined and this would be used in further investigations to determine the strength parameters of the dental restorative materials.

6.2 Methods

The size of the flexural specimens were 25 mm length and 5 mm width. The thickness of the specimens was varied according to a span/depth ratio. A group of specimens of span/depth ratios of 2:1 (Specimens of 5 mm thickness and span of 10 mm), 5:1 (Specimens of 4 mm thickness and span of 20 mm), 7.5:1 (Specimens of 2 mm thickness and span of 15 mm) and 20:1 (Specimens of 1 mm thickness and span of 20 mm) were prepared. Four crosshead speeds were evaluated for each specimen size. These were 0.1 mm per minute, 0.5 mm per minute, 1 mm per minute and 10 mm per minute. Thirty specimens were prepared for each test and a total of 480 specimens were tested.

The specimens were prepared in accordance to the procedure described in chapter three. All the tests were carried out using an Instron Universal testing machine (Model 1195) as shown in Photograph J. The data was analysed by the computer program described in chapter four.

Data from the mechanical test for each type of material was analysed by the Weibull distribution. As previously mentioned this was done by the computer. The output of the program such as Weibull modulus, standard error of modulus, characteristic strength and stress at various levels of failure probability were recorded. A typical set of data and the print out of the Weibull analysis is shown in the appendix B.

Mean strength, percentage of deviation coefficient and stress at various levels of failure probability from the Normal distribution were also calculated. Stresses at various levels of probability of failure from the Weibull distribution and the Normal distribution were compared.

The results of all the mechanical tests for all types of material under investigation were put in the form of Tables for the analysis by the Weibull distribution and Normal distribution. A graphical representation of the results of the Weibull distribution is shown in the Figures.

6.3 Results and Discussions

The results for the flexural strength of Occlusin are reported in three parts. In the first part, the effect of crosshead speeds on the flexural strength were investigated at each Span/Depth ratio. The results are shown in Tables 6.3.1, 6.3.2, 6.3.3 and 6.3.4 and Figures 6.3.1, 6.3.2, 6.3.3 and 6.3.4 . Span/Depth ratios of 2, 5, 7.5 and 20 were used in the investigation. Secondly, the effect of the Span/Depth ratio on the flexural strength was investigated

TABLE 6.3.1

Summary of Weibull analysis-Flexural strength of Occlusin for the specimens of span/depth = 2 which are tested at various crosshead speed.

Crosshead Speed (mm/mim)	0.1	0.5	1.0	10.0
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	13.9 162.8 0.56 0.96	11.3 193.2 0.18 0.96	11.7 186.6 0.48 0.96	11.1 174.1 0.33 0.98
Mean Strength+ Deviation Coefficient (%)	157.1 7.8	185.1 9.5	179.0 9.3	166.7 9.7
Stress+ at Failure Probability				
0.01% - Weibull Normal	83.9 148.8	85.5 173.2	84.8 167.8	76.0 155.8
1% - Weibull Normal	116.9 151.9	128.6 177.6	125.9 171.9	115.1 159.8
99.99% - Weibull Normal	181.7 165.4	221.1 197.0	212.6 190.2	199.7 177.6

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-Very Highly significant difference between strength and crosshead speed ($P<0.001$).

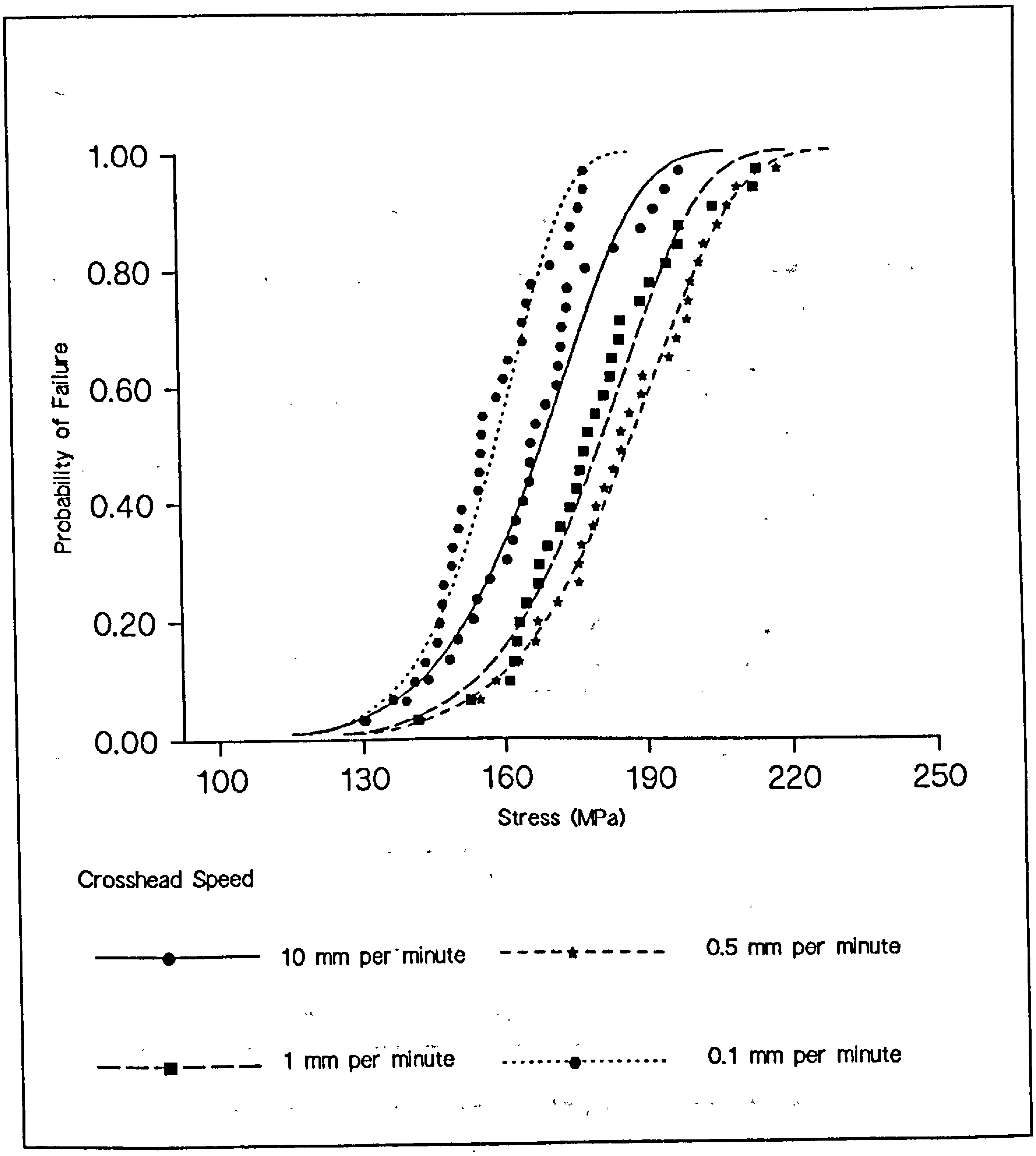


FIGURE 6.3.1
Flexural strength of Occlusin-Probability of failure versus flexural stress for the specimens of span/depth ratio = 2 which are tested at various crosshead speeds. Specimens are bench dried for 7 days prior testing.

TABLE 6.3.2

Summary of Weibull analysis-Flexural strength of Occlusin for the specimens of span/depth = 5 which are tested at various crosshead speed.

Crosshead Speed (mm/mim)	0.1	0.5	1.0	10.0
Weibull Modulus Characteristic Strength⁺ Standard Error of Modulus Coeff. of Correlation	14.3 143.4 0.47 0.97	17.2 144.6 0.50 0.98	9.8 145.5 0.28 0.98	14.4 148.4 0.64 0.95
Mean Strength⁺ Deviation Coefficient (%)	138.6 7.5	140.5 6.3	138.6 10.8	143.4 7.5
Stress⁺ at Failure Probability				
0.01% - Weibull Normal	75.4 131.6	84.6 134.5	56.7 128.5	78.3 136.1
1% - Weibull Normal	104.1 134.2	110.6 136.7	90.9 132.2	107.9 138.8
99.99% - Weibull Normal	159.6 145.6	158.0 146.5	170.1 148.7	165.0 150.7

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-Very highly no significant difference between strength and crosshead speed (P=0.55).

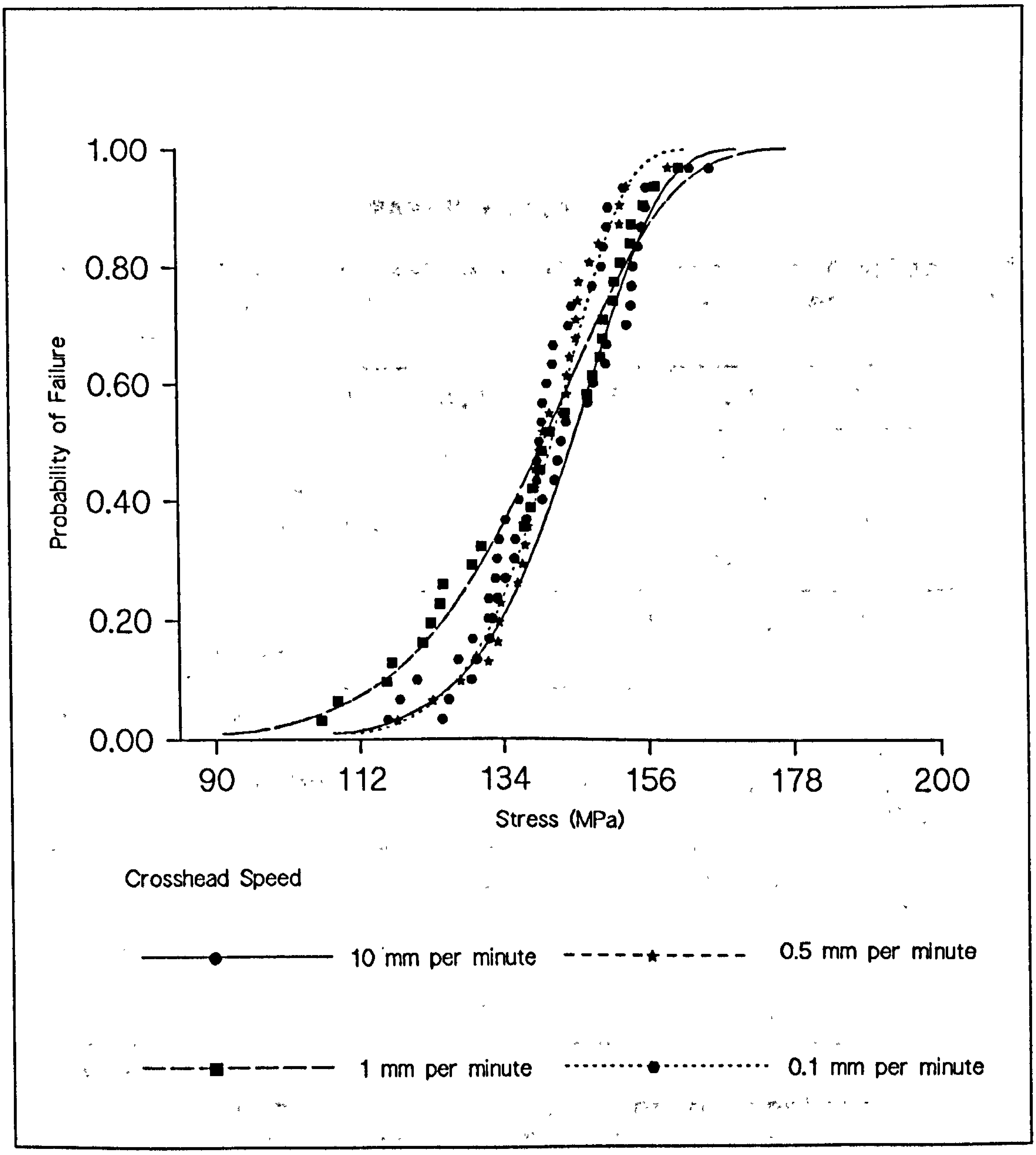


FIGURE 6.3.2

Flexural strength of Occlusin-Probability of failure versus flexural stress for the specimens of span/depth ratio = 5 which are tested at various crosshead speeds. Specimens are bench dried for 7 days prior testing.

TABLE 6.3.3

Summary of Weibull analysis-Flexural strength of Occlusin for the specimens of span/depth = 7.5 which are tested at various crosshead speed.

Crosshead Speed (mm/mim)		0.1	0.5	1.0	10.0
Weibull Modulus		13.2	11.2	10.8	10.6
Characteristic Strength+		136.9	139.7	147.8	143.3
Standard Error of Modulus		0.48	0.35	0.77	0.49
Coeff. of Correlation		0.96	0.97	0.88	0.95
Mean Strength+		131.9	133.5	141.3	137.0
Deviation Coefficient (%)		8.3	9.4	10.0	9.9
Stress+ at Failure Probability					
0.01%	- Weibull	68.1	61.3	63.0	61.4
	Normal	124.5	125.0	131.8	127.8
1%	- Weibull	96.6	92.6	96.5	93.1
	Normal	127.2	128.2	135.3	131.2
99.99%	- Weibull	153.7	160.2	170.3	165.4
	Normal	139.3	142.0	150.8	146.2

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-Significant difference between strength and crosshead speed (P<0.05).

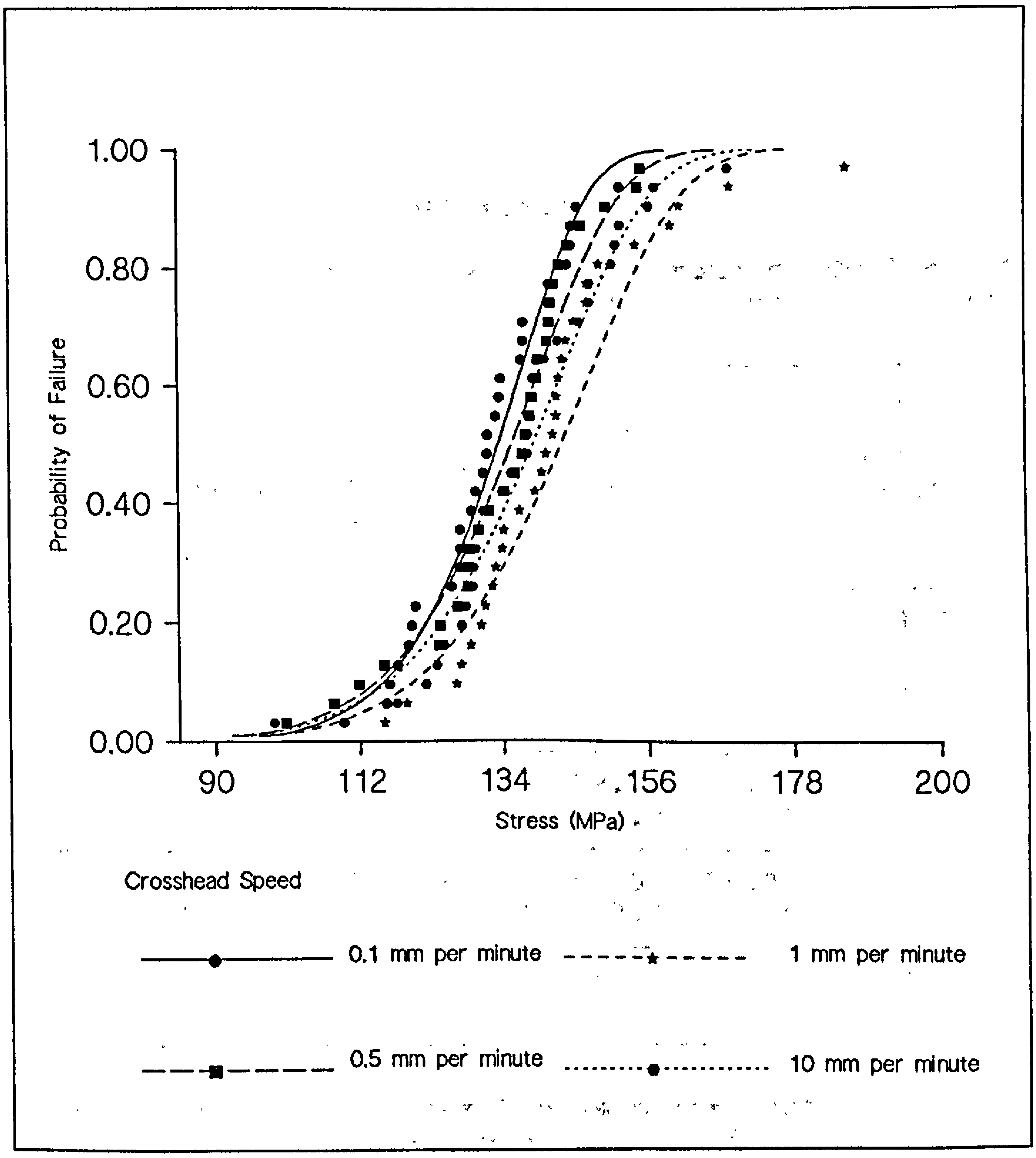


FIGURE 6.3.3
Flexural strength of Occlusin-Probability of failure versus flexural stress for the specimens of span/depth ratio = 7.5 which are tested at various crosshead speeds. Specimens are bench dried for 7 days prior testing.

TABLE 6.3.4

Summary of Weibull analysis-Flexural strength of Occlusin for the specimens of span/depth = 20 which are tested at various crosshead speed.

Crosshead Speed (mm/mim)	0.1	0.5	1.0	10.0
Weibull Modulus	9.0	8.4	8.4	9.6
Characteristic Strength+	113.6	119.4	128.3	129.8
Standard Error of Modulus	0.20	0.41	0.45	0.33
Coeff. of Correlation	0.99	0.94	0.92	0.97
Mean Strength+	107.8	112.9	121.4	123.5
Deviation Coefficient (%)	11.8	11.9	12.4	11.0
Stress+ at Failure Probability				
0.01% - Weibull	40.9	39.7	43.0	49.5
Normal	99.2	103.8	111.2	114.3
1% - Weibull	68.2	68.9	74.3	80.2
Normal	102.4	107.2	115.0	117.7
99.99% - Weibull	134.5	143.0	153.9	152.3
Normal	116.4	122.0	131.6	132.7

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-Very highly significant difference between strength and crosshead speed (P<0.001).

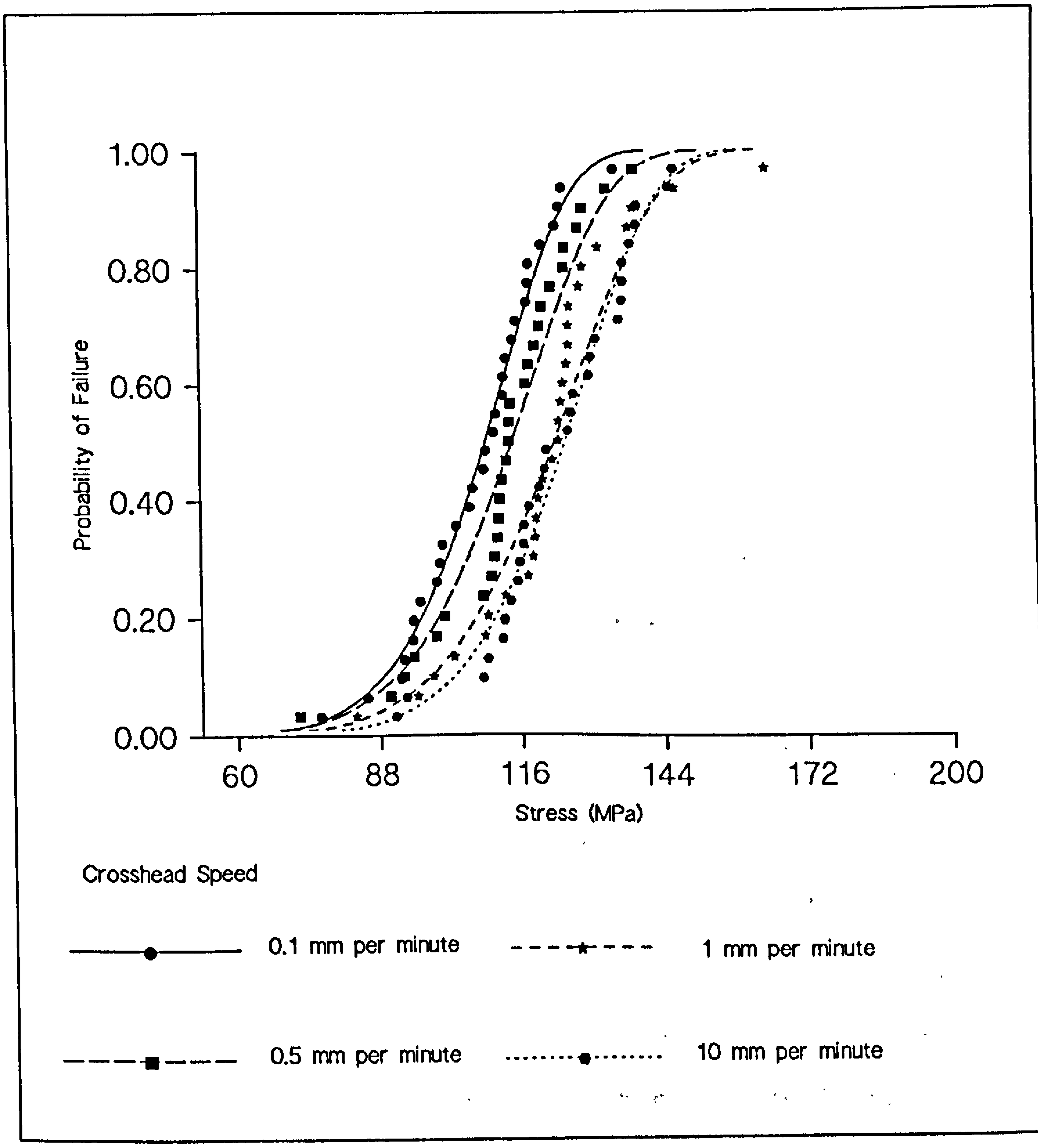


FIGURE 6.3.4
Flexural strength of Occlusin-Probability of failure versus flexural stress for the specimens of span/depth ratio = 20 which are tested at various crosshead speeds. Specimens are bench dried for 7 days prior testing.

TABLE 6.3.5

Summary of Weibull Analysis-Flexural Strength of Occlusin for the specimens* of various span/depth ratios which are tested at crosshead speeds 10mm/min.

Span/Depth Ratio		2.0	5.0	7.5	20.0
Weibull Modulus		11.1	14.4	10.6	9.6
Characteristic Strength+		174.1	148.4	143.3	129.8
Standard Error of Modulus		0.33	0.64	0.49	0.33
Coeff. of Correlation		0.98	0.95	0.95	0.97
Mean Strength+		166.7	143.4	137.0	123.5
Deviation Coefficient (%)		9.7	7.5	9.9	11.0
Stress+ at Failure Probability					
0.01%	- Weibull	76.0	78.3	61.4	49.5
	Normal	155.8	136.1	127.8	114.3
1%	- Weibull	115.1	91.9	93.1	80.2
	Normal	159.8	138.8	131.2	117.7
99.99%	- Weibull	199.7	165.0	165.4	152.3
	Normal	177.6	150.7	146.2	132.7

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-Very highly significant difference between strength and span/depth ratio(P<0.001).

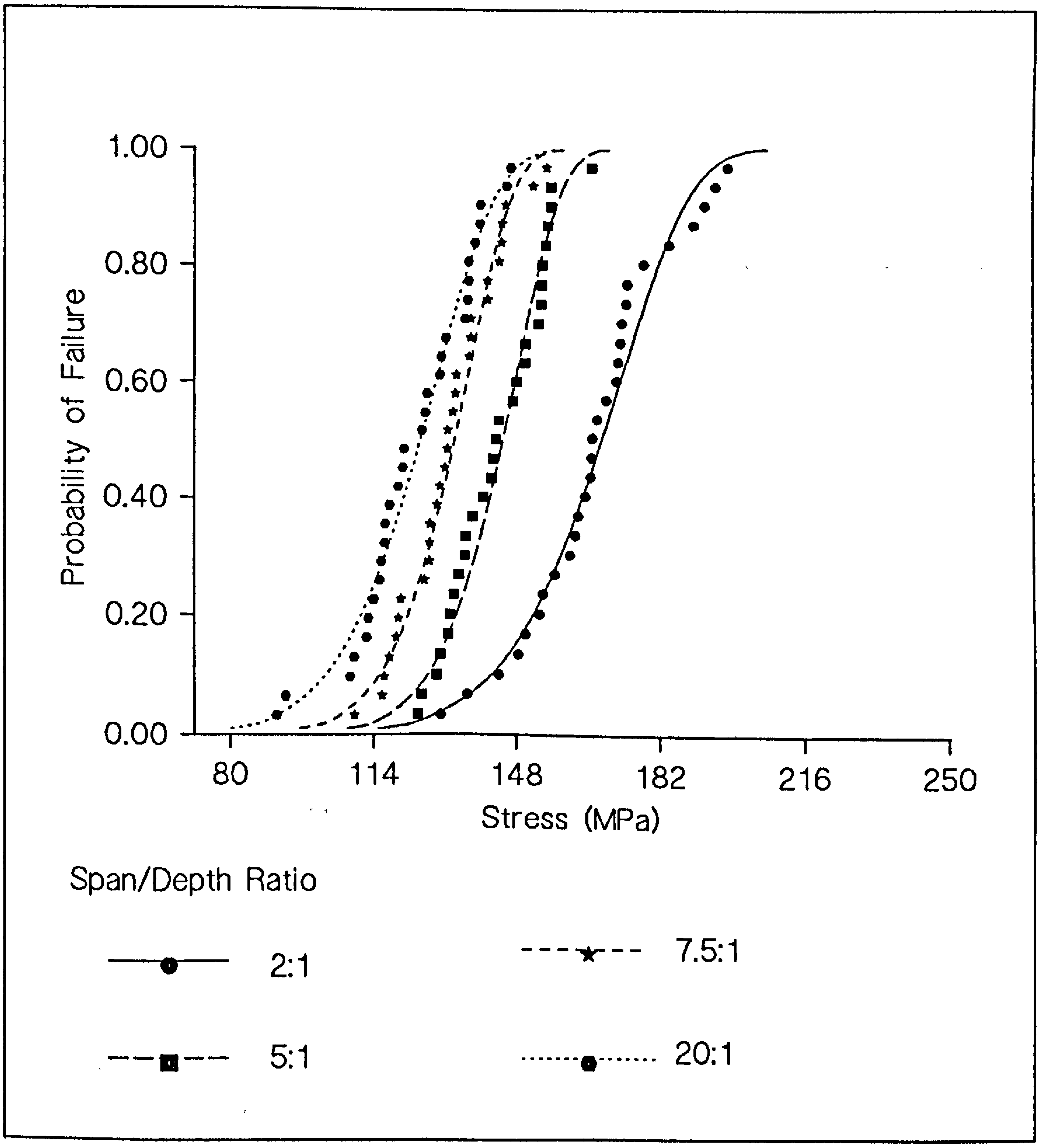


FIGURE 6.3.5
Flexural strength of Occlusin-Probability of failure versus flexural stress for the specimens of various span/depth ratios which are tested at crosshead speeds 10mm/min.
Specimens are bench dried for 7 days prior testing.

TABLE 6.3.6

Summary of Weibull Analysis-Flexural Strength of Occlusin for the specimens* of various span/depth ratios which are tested at crosshead speeds 1mm/min.

Span/Depth Ratio	2.0	5.0	7.5	20.0
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	11.7 186.6 0.48 0.96	9.8 145.5 0.28 0.98	10.8 147.8 0.77 0.88	8.4 128.3 0.45 0.92
Mean Strength+ Deviation Coefficient (%)	179.0 9.3	138.6 10.8	141.3 10.0	121.4 12.4
Stress+ at Failure Probability				
0.01% - Weibull Normal	84.8 167.8	56.7 128.5	63.0 131.8	43.0 111.2
1% - Weibull Normal	125.9 171.9	90.9 132.2	96.5 135.3	74.3 115.0
99.99% - Weibull Normal	212.6 190.2	170.1 148.7	170.3 150.8	153.9 131.6

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-Very highly significant difference between strength and span/depth ratio($P<0.001$).

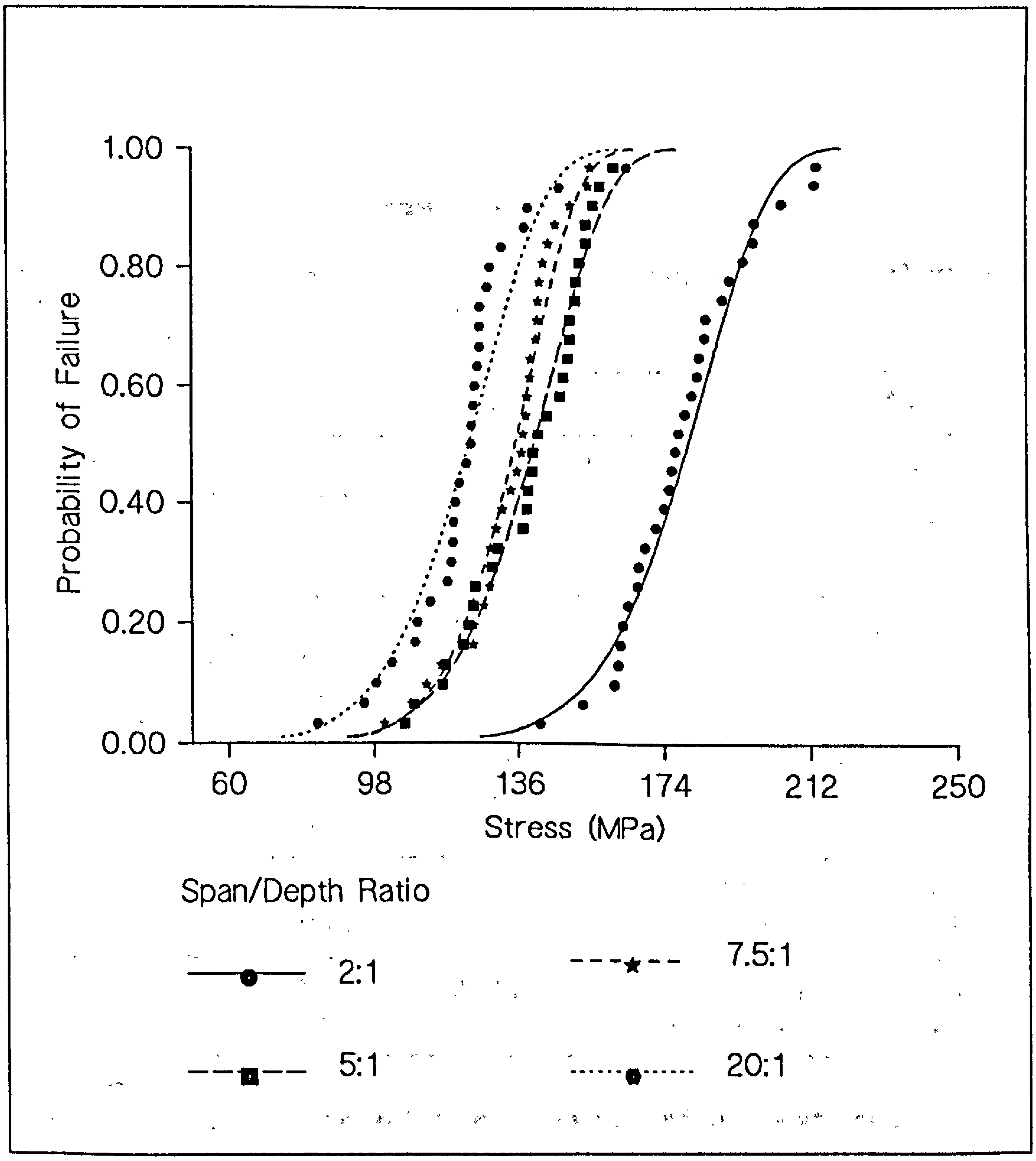


FIGURE 6.3.6

Flexural strength of Occlusin-Probability of failure versus flexural stress for the specimens of various span/depth ratios which are tested at crosshead speeds 1mm/min.

Specimens are bench dried for 7 days prior testing.

TABLE 6.3.7

Summary of Weibull Analysis-Flexural Strength of Occlusin for the specimens* of various span/depth ratios which are tested at crosshead speeds 0.5mm/min.

Span/Depth Ratio	2.0	5.0	7.5	20.0
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	11.3 193.2 0.18 0.99	17.2 144.6 0.50 0.98	11.2 139.7 0.35 0.97	8.4 119.4 0.41 0.94
Mean Strength+ Deviation Coefficient (%)	185.1 9.5	140.5 6.3	133.5 9.4	112.9 11.9
Stress+ at Failure Probability				
0.01% - Weibull Normal	85.5 173.2	84.6 134.5	61.3 125.0	39.7 103.8
1% - Weibull Normal	128.6 177.6	110.6 136.7	92.6 128.2	68.9 107.2
99.99% - Weibull Normal	221.1 197.0	158.0 146.5	160.2 142.0	143.3 122.0

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-Very highly significant difference between strength and span/depth ratio(P<0.001).

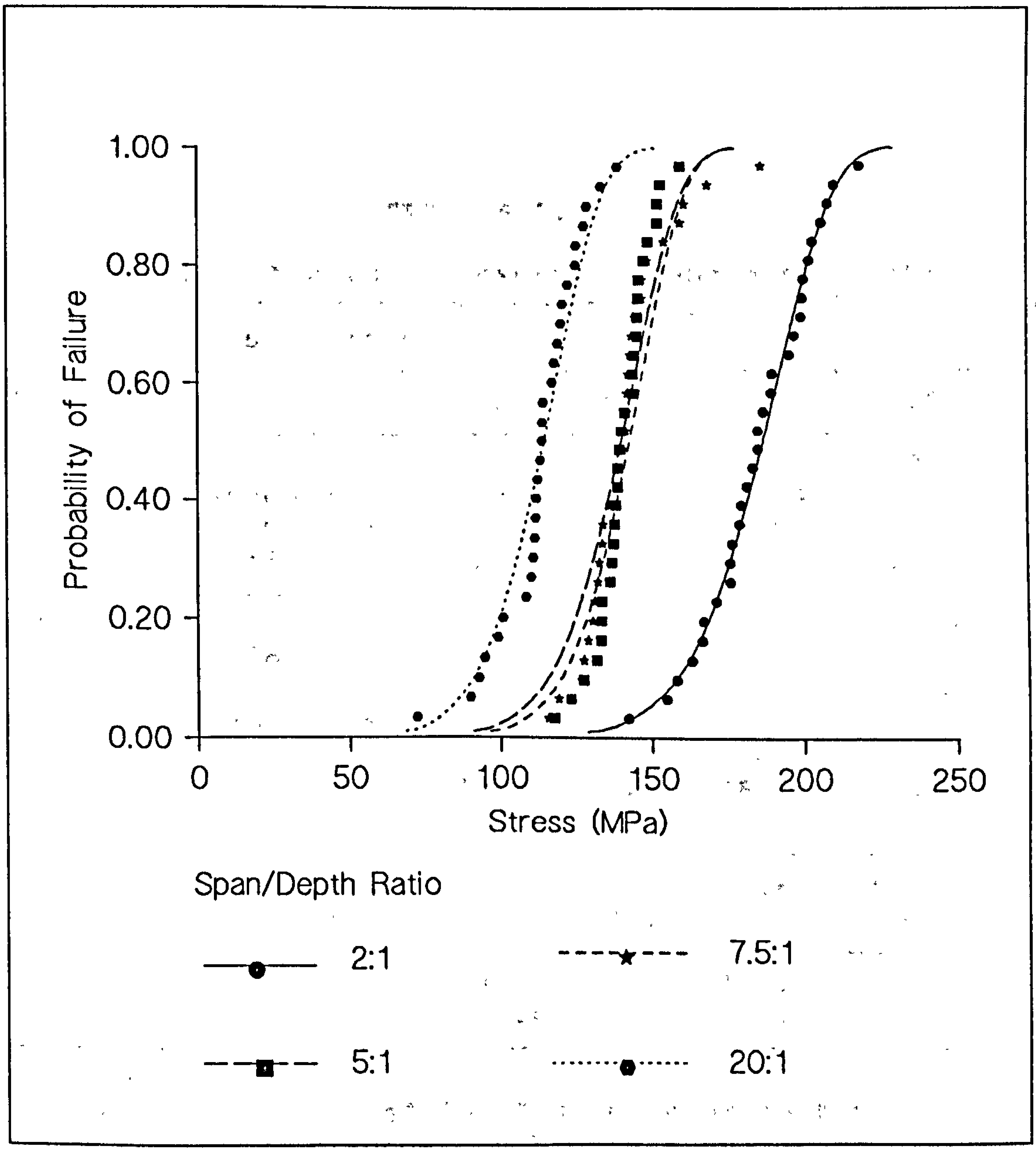


FIGURE 6.3.7
Flexural strength of Occlusin-Probability of failure versus flexural stress for the specimens of various span/depth ratios which are tested at crosshead speeds 0.5mm/min.
Specimens are bench dried for 7 days prior testing.

TABLE 6.3.8

Summary of Weibull Analysis-Flexural Strength of Occlusin for the specimens* of various span/depth ratios which are tested at crosshead speeds 0.1mm/min.

Span/Depth Ratio		2.0	5.0	7.5	20.0
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation		13.9 162.8 0.56 0.96	14.3 143.4 0.47 0.97	13.2 136.9 0.48 0.96	9.0 113.6 0.20 0.99
Mean Strength+ Deviation Coefficient (%)		157.1 7.8	138.6 7.5	131.9 8.3	107.8 11.8
Stress+ at Failure Probability					
0.01%	- Weibull Normal	83.9 148.8	75.4 131.6	68.1 124.5	40.9 99.2
1%	- Weibull Normal	116.9 151.9	104.1 134.2	96.6 127.2	68.2 102.4
99.99%	- Weibull Normal	181.7 165.4	159.6 145.6	153.7 139.3	134.5 116.4

+ unit in Mpa.
* Specimens are bench dried for 7 days prior testing.
Oneway analysis of variance-Very highly significant difference between strength and span/depth ratio(P<0.001).

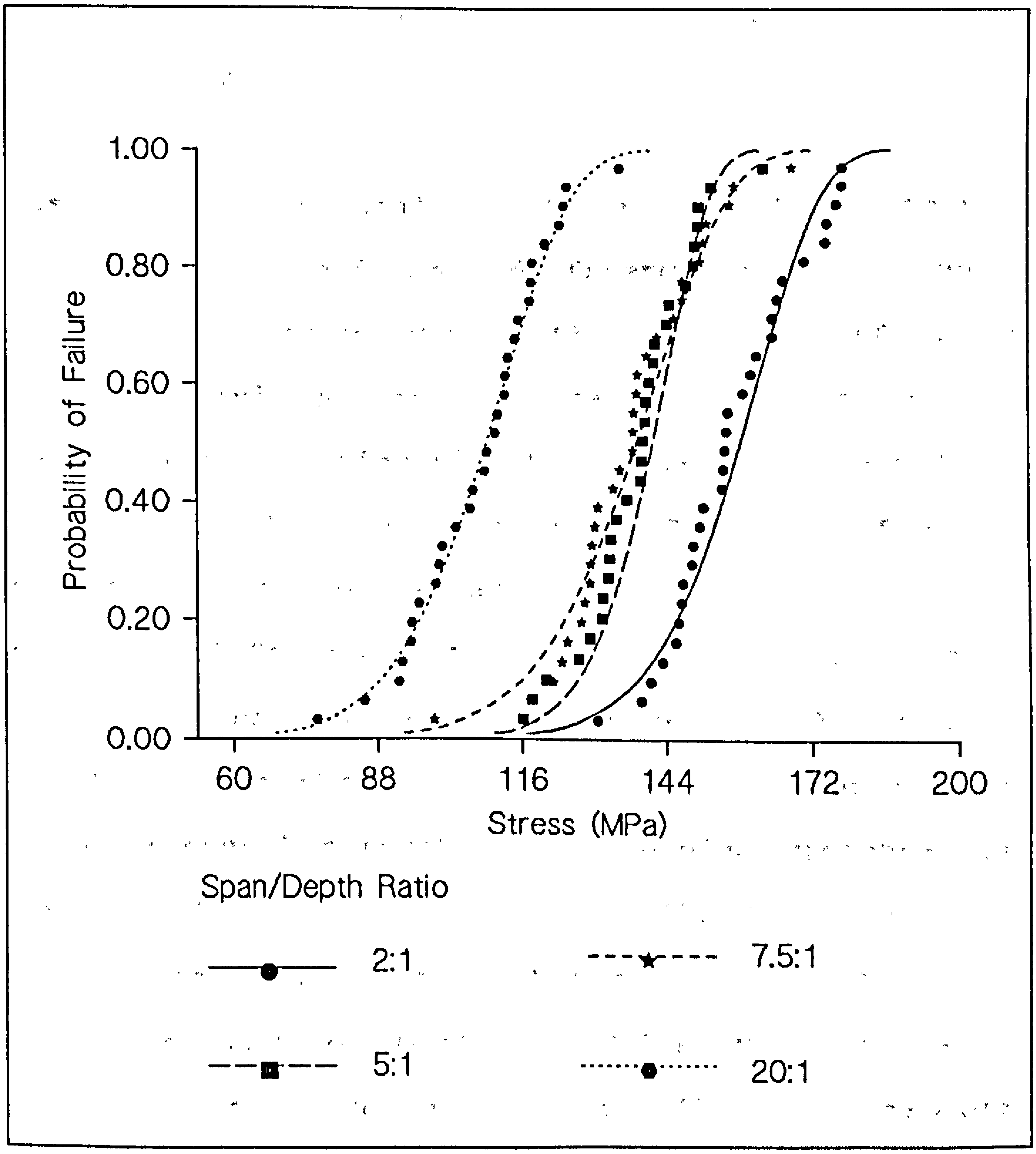


FIGURE 6.3.8
Flexural strength of Occlusin-Probability of failure versus flexural stress for the specimens of various span/depth ratios which are tested at crosshead speeds 0.1mm/min.
Specimens are bench dried for 7 days prior testing.

at each crosshead speed. The results are shown in Tables 6.3.5, 6.3.6, 6.3.7 and 6.3.8 and Figures 6.3.5, 6.3.6, 6.3.7 and 6.3.8 .

It has been shown by analysis of variance (ANOVA) that there is a highly significant difference between the mean strengths for varying span/depth ratios ($p<0.001$). Oneway analysis of variance for each span/depth ratio showed that there was a highly significant difference between the mean flexural strengths for changing crosshead speeds for span/depth ratios of 2 and 20 ($P<0.001$). There is a significant difference between the mean flexural strengths for changing crosshead speed and a span/depth ratio of 7.5 ($P<0.05$). However there is no significant difference between the mean flexural strengths for changing crosshead speeds for a span/depth ratio of 5 ($P=0.55$). This shows that a specimen with a span/depth ratio of 5 does not affect the flexural strength of Occlusin. While specimens of other span/depth ratios do affect the flexural strength of Occlusin. This is not in agreement with the reports (Shervlin, Lindenthal:1959, Jones, Wilson:1972) that have been mentioned in chapter two. It has been stated that the mean flexural strengths of a specimen of span/depth ratios ranging from 5 to 15 do not vary significantly.

Figure 6.3.1 shows graphically the results for the specimens of span/depth ratio of 2:1 that have been tested at various crosshead speeds. The Weibull curves of all tests are separated from each other. This shows the strengths of each group are different from each other. Thus it shows the effect of crosshead speed on flexural strength of Occlusin when the specimens of span/depth ratio of 2:1 were tested. The characteristic strength and mean strength decreased as the crosshead speed was increased except for the slowest speed (i.e 0.1 mm per minute). The characteristic strength and mean strength of the slowest speed are the lowest of the series. When the flexural test was carried out at a very slow rate of strain, it was observed during the test that the mode of failure is less catastrophic than the test at the other crosshead speeds. The catastrophic failure increased as the crosshead speed increased. A low value of flexural strength was calculated for the specimens that were tested at a crosshead speed of 0.1 mm per minute and this may be due to some plastic behaviour at failure. It is shown by the higher value of Weibull modulus calculated for this test. This indicates that the specimens tested at a crosshead speed of 0.1 mm per minute are less brittle than the specimens of the other tests. The plastic behaviour is may be due to partially cured dimethacrylate molecules as incomplete polymerization may lower the strength (Ruyther and Svendsen:1978, Ruyther and Oysaed:1982, Asmussen:1882). A low flexural strength was also reported for the specimens tested at a crosshead speed 10 mm per minute when compared to the strength of the specimens that were tested at a crosshead speed of 0.5 and 1 mm per minute. As the rate of strain increases, plastic behaviour may become less significant and a failure due to the effect of flaws may become significant. A failure may occur when the most critical flaw has been initiated (Mclean:1979). However at very high strain rate, the characteristic at failure may be governed by the other factor(s) as it may reflect a condition for a toughness test. It is felt that a crosshead speed of 10 mm per minute may not suitable for the flexural test. The results of the tests that have been carried out at a crosshead speeds of 0.5 and 1 mm per minute, Table 8.3.1 shows that the mean flexural strengths of Occlusin specimens tested at a crosshead speeds 0.5 and 1 mm per minute are approximately the same. The Tukey range test has showed that these mean flexural strengths are not significantly different (p>0.05). The value of Weibull moduli for these tests are the same. This means that the specimens are of the same degree of brittleness. This could also indicate the reliability of the test as it gave the same value of Weibull modulus. The performance of the specimens of these tests are also the same, therefore it may be suggested that a crosshead speed of 0.5 or 1 mm per minute may be suitable for the flexural test.

Table 6.3.2 and Figure 6.3.2 show the results for the specimens of span/depth ratio 5:1 that have been tested at various crosshead speeds. There is no significant difference between the mean strength for varying crosshead speed (one-way, p=0.55). This shows that crosshead speed does not affect the flexural strength when specimens of a span/depth ratio of 5:1 are used. When the specimens of span/depth ratio of 5:1 were tested, the mode of failure may be due to the plastic flow. This has been discussed in the previous paragraph i.e that partially cured molecules lead to a plastic flow when a crosshead speed of 0.1 mm per minute is used to test the specimens. As the span/depth ratio increases, this behaviour may be became more significant. At a higher crosshead speed, a failure that has been characterised by the initiation of a critical flaw may be become less significant when compared to the plastic flow behaviour. That may be the reason why all the tests produced the same mean strength. However the performance of the specimens that were tested at a crosshead speed of 0.5 mm per minute was better than the performances of the other tests. This may due to the high Weibull modulus. This also can be explained by using the value of deviation coefficients. The deviation coefficient of the test carried out at 0.5 mm per minute is the lowest. This shows the data was less scattered when the ~~the~~ specimens were tested at crosshead speed of 0.5 mm per minute. Therefore a crosshead speed of 0.5 mm per minute may be suitable for the flexural test. This is in agreement with the conclusion stated for the test carried out at span\depth ratio of 2:1.

Table 6.3.3 and Figure 6.3.3 show the results for the specimens of span/depth ratio 7.5:1 that were tested at various crosshead speeds. There is a significant difference between the mean strengths for varying crosshead speed (one-way, $p<0.05$). This shows that crosshead speed does affect the flexural strength when specimens of span/depth ratio of 7.5:1 are used. However the Tukey range test shows that there is no variation between the mean flexural strengths of the specimens that have been tested at a crosshead speeds 0.1 and 0.5 mm per minute ($p>0.05$). Tukey range test also shows there is no variation between the mean flexural strengths of the specimens that have been tested at a crosshead speeds 1 and 10 mm per minute ($p>0.05$). This effect is clearly shown in Figure 6.3.3, where the Weibull curves for the tests of a crosshead speed of 0.1 and 0.5 mm per minute are not separated from each other. This is also shown for the tests at crosshead speeds of 1 and 10 mm per minute. The flexural strength of the specimens of the latter group is found to be higher than the flexural strength of the former group. In addition the Weibull moduli of the specimens for the tests that have been carried out at a crosshead speeds of 1 and 10 mm per minute are less than the Weibull moduli of the specimens for the test that have been carried out at a crosshead speeds of 0.1 and 0.5 mm per minute. This shows that the specimens tested at crosshead speeds of 0.1 and 0.5 mm per minute are less brittle than the specimens tested at other crosshead speeds. The reason for this may be that the plastic flow behaviour is still significant at span/depth ratio of 7.5:1 when the tests are carried out at a crosshead speeds of 0.1 and 0.5 mm per minute. However at a higher crosshead speeds, it seems the effect of plastic flow is diminished. It can be seen from high flexural strengths and low Weibull moduli. As has been mentioned previously plastic flow behaviour at failure may be become more significant with an increase in span/depth ratio. This disagreement may be due to the specimen size. The depth of the specimen used in this experiment was less than the depth of the specimen used in the previous tests. In this case, the polymerization may be almost complete as the depth of the specimen is quite thin. So the mode at failure for the tests carried out at a crosshead speed of 1 and 10 mm per minute may be due to flaw initiation. However the correlation coefficient for this test is poor when compared to the value of correlation for the tests carried out at a crosshead speed of 0.1 and 0.5 mm per minute. This means that the data of the specimens for the tests carried out at a crosshead speed 1 and 10 mm per minute do not give a good fit to the Weibull distribution equation. Thus the tests at crosshead speeds 1 and 10 mm per minute for the specimens of span/depth ratio 7.5:1 are not suitable. The correlation coefficient for the tests carried out at crosshead speeds 0.5 was the highest. The data from this test gave a better fit to the Weibull distribution than other tests. Therefore the test carried out at 0.5 mm per minute may be used for the flexural test.

Table 6.3.4 and Figure 6.3.4 show the results of the specimens for the span/depth ratio 20:1 that have been tested at various crosshead speeds. There is a highly significant difference between the mean strengths for varying crosshead speed (one-way, $p<0.001$). This shows that crosshead speed does affect the flexural strength when specimens of span/depth ratio of 20:1 are used. The Tukey range test shows the mean strength for the tests carried out at crosshead speeds 1 and 10 mm per minute are not significantly different ($p>0.05$). This is clearly shown in Figure 6.3.4 where the Weibull curve for the specimens of span/depth ratio of 20:1 that have been tested at crosshead speeds 1 mm per minute and 10 mm per minute are approximately close to each other.

The characteristic strengths for these tests are also approximately the same. The characteristic strength of the specimens for the test carried out at a crosshead speed of 0.1 mm per minute is also approximately equal to the characteristic strength of the specimens for the test carried out at a crosshead speed of 0.5 mm per minute. However the results for the tests carried out at a crosshead speeds of 0.5 and 1 mm per minute are doubtful because their correlation coefficients are very poor when compared to the tests carried out at a crosshead speeds of 0.1 and 10 mm per minute. Because the Weibull modulus of the tests carried out at crosshead speeds of 0.1 and 10 mm per minute are the same, it is expected that the characteristic strength and mean strength of the specimens tested at a crosshead speeds 0.5 and 1 mm per minute should be approximately the same as for the specimens that have been tested at a crosshead speeds of 0.1 and 10 mm per minute. In addition, because of the very thin specimens were used in this experiment, the mode at failure for all the tests may due to the plastic flow behaviour as mentioned in the previous paragraph

For the effect on the flexural strength of Occlusin of varying span/depth ratio, one-way analysis of variance showed that there was a very highly significant difference between the mean strengths for varying span/depth ratios ($P<0.001$). However it is shown in Figures 6.3.5, 6.3.6, 6.3.7 and 6.3.8 that the curves for span/depth ratios 5:1 and 7.5:1 are drawing closer to each other as the crosshead speed decreases from 10 mm per minute to 0.1 mm per minute. The difference between the mean strength of the test carried out at span/depth ratio 5:1 and 7.5:1 is the smaller when the test was carried out at a crosshead speed of 0.5 and 1 mm per minute. This is clearly shown in the Figures 6.3.6 and 6.3.7 where the Weibull curves for the flexural strength of the specimens of span/depth ratios of 5:1 and 7.5:1 that have been tested with a crosshead speeds 0.5 and 1 mm per minute are very close to each other. This shows the crosshead speeds of 0.5 and 1 mm may be used to test the flexural strength of specimens of span/depth ratios ranging from 5:1 to 10:1 . The Weibull curve for the specimens of span/depth ratio 10:1 was not tested. But according to the mode of the tests, the Weibull curve for the specimens of a span/depth ratio 10:1 is thought to be closer to the Weibull curve for the specimens of a span/depth ratio 7.5:1 rather than to the curve for the specimens of span/depth ratio 20:1. The crosshead speed of 0.5 mm per minute may be the optimum crosshead speed for the flexural test for specimens of span/depth ratios of ranging from 5:1 to 10:1. This crosshead speed is selected because the data from the tests are well fitted to Weibull distribution when compared to the tests carried out at a crosshead speed of 1 mm per minute, particularly for the specimens of span/depth ratio of 7.5:1. This is shown by a poor correlation coefficient of the test for the specimens of span/depth ratio of 7.5:1 when a crosshead speed of 1 mm per minute was used. A low correlation coefficient indicates that the data does not fit the Weibull distribution very well. As a result, a crosshead 0.5 mm per minute will produce the most reliable results for the test carried out at span/depth ratios between 5:1 and 10:1.

Tables 6.3.5 shows the results for the tests that have been carried out at a crosshead speed of 10 mm per minute. The mean flexural strength decreases as span/depth ratio increases. At a span/depth ratio of 2:1, the mean flexural strength of the specimens is higher because of the catastrophic failures that have been discussed in the beginning ~~begining~~ of this chapter. As span/depth ratio increases, the catastrophic failure becomes less significant and plastic flow behaviour becomes more accessible and less stress is required to propagate a crack. This may be the reason why the flexural strength decreases as span/depth ratios increases. This effect is graphically illustrated in Figure 6.3.5 . Table 6.3.8 and Figure 6.3.8 are also show the same behaviour as described for Table and Figure 6.3.5 . The flexural strength of the tests carried out at a crosshead speed of 0.1 mm per minute decreases, as span/depth ratio increases.

6.4 Summary and Conclusion

A crosshead speed of 0.5 mm per minute is found to be the optimum crosshead for the flexural test. It may produce reliable results when specimens of span/depth ratios between 5:1 and 10:1 are used in the test. This finding is not in agreement with the results of an earlier worker (Shervlin, Lindenthal:1959, Jones, Wilson:1972). They said that there was no significant difference between the mean flexural strengths when specimens were tested at a span/depth ratios between 5:1 to 15:1.

CHAPTER SEVEN

A RELATIONSHIP BETWEEN NORMAL AND WEIBULL PARAMETERS

7.1 Introduction

The results of the previous investigation i.e in chapters 4, 5 and 6, showed that the strength of the material varies with the test parameters such as crosshead speed and specimen size. Strength analysis showed the effect of crosshead speed and specimen size on compressive, diametral tensile and flexural strength of the materials under test. The assessment made by the Weibull analysis was the same as that described by the Normal analysis. This may due to the fact that the number of specimens was large enough. As a result,it fits both the Normal analysis and the Weibull analysis. However the stress predicted by Weibull analysis at a lower probability of failure was better than Normal analysis as the stress predicted by Normal analysis is over estimated. At a low level of failure probability, (0.01%), the lowest stress is estimated by Weibull analysis. The stress estimated by student distribution gave the highest value. In order to estimate the stress at 1% failure probability or at any others lower probabilities, Weibull distribution is a much safer method to use as it gives a lower value. At a higher level of failure probability (99.99%), the stress estimated by Normal distribution gave the highest value and Student Distribution gave the lowest value. The Weibull prediction however is less than Normal prediction. Therefore the Weibull distribution is also can be used to predict the true strength of the material. Nevertheless Weibull prediction may consider the noble one if Normal prediction at a higher probability of failure is suspected to give an over estimated true strength of the material. Thus Weibull analysis is found to be a safer method used in predicting the stress at a lower failure probability level when compared to the Normal analysis. And it also may be used to estimate the true strength of a material.

Two relationships were discovered with the results reported in chapters 4, 5 and 6. The relationship between the percentage of deviation coefficient and the Weibull modulus and the relationship between the percentage of deviation coefficient and the mean stress divided by characteristic stress (stress constant). These two relationships are found to be useful in predicting the value of Weibull modulus and the characteristic strength of a material. The Weibull modulus and characteristic strength for a batch of specimens of less than 30 could be estimated by using its mean strength and the percentage of deviation coefficient. This relationships is designed to be used as a supplementary method in a standard of testing where a stress at any level of failure probability or a probability of failure at any arbitrary stress could be estimated by using Weibull distribution equation.

Most standards of testing (BS:5199:1971, BS:2938:1985, BS:4722:1971, BS:7214:1989, ISO:4049) suggested 5 or at most 10 specimens to be used to assess a strength of a material as this has been discussed in chapter two. The strength of a material is reported as a mean value of each individual strength and a standard deviation. Weibull analysis may not be given a reliable results when a small number of specimen is tested. At least 30 specimens are required in order to obtain a reliable result (Trustrum and Jayatilaka:1979, McCabe and Walls:1986, McCabe and Carrick:1986). However by using the relationships written in equations 7.1 and 7.2, the Weibull modulus and characteristic strength of a material can be estimated by using the mean and standard deviation. Therefore the test of a large number of specimens may be avoided.

7.2 The Relationship between Weibull Modulus and Coefficient Deviation

The values of Weibull moduli and deviation coefficient (%) were taken from all the previous results. The value of Weibull modulus was plotted against deviation coefficient (%). The result of this plot is shown in Figure 7.1. The curve was plotted using least square method and it gave a high value of correlation coefficient. This shows a good correlation between the data and the equation. The equation of the curve is shown below.

$$Y = 99.2 \; (X^{-0.973}) \qquad (7.1)$$

where Y is the deviation coefficient (%) and X is the Weibull modulus.

7.3 The Relationship between Mean Strength, Characteristic Strength and Coefficient Deviation

The values of mean strength, characteristic strength and deviation coefficients(%) were taken from the previous results. The value of mean strength was divided by the value of characteristic strength. This value was than plotted against deviation coefficient(%). The graph of this plot is shown in Figure 7.2. It shows a linear relationship. The equation of this linear relationship was found to be:-

$$Y = 0.995 - 0.04X \qquad (7.2)$$

where Y is mean strength divide by characteristic strength and X is the deviation coefficients(%).

The graph was plotted by using least square method. High correlation coefficient was obtained with the equation 7.2. This shows a good fit between data points and the equation.

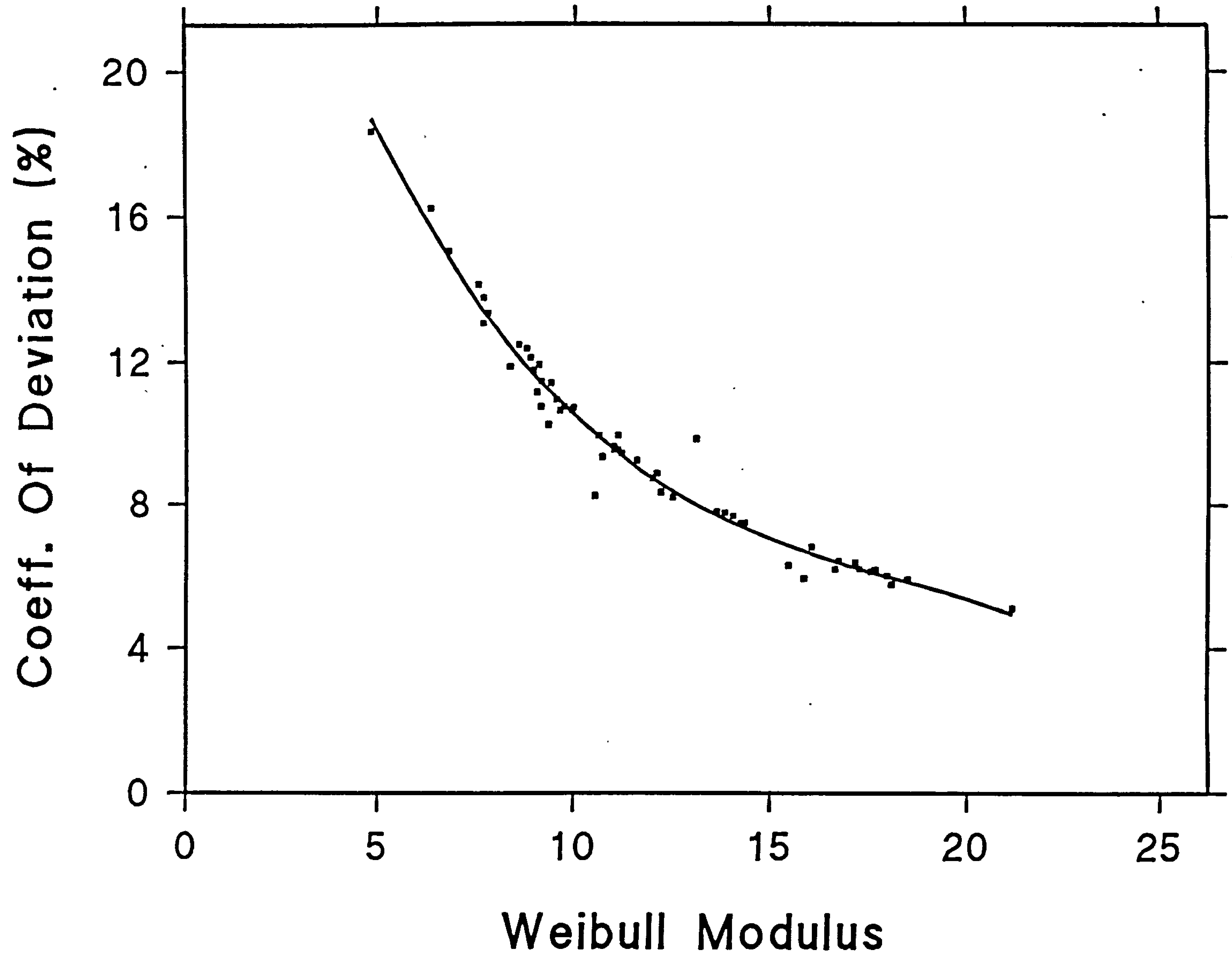


FIGURE 7.1
A relationships between coefficient deviation(%) and Weibull modulus.

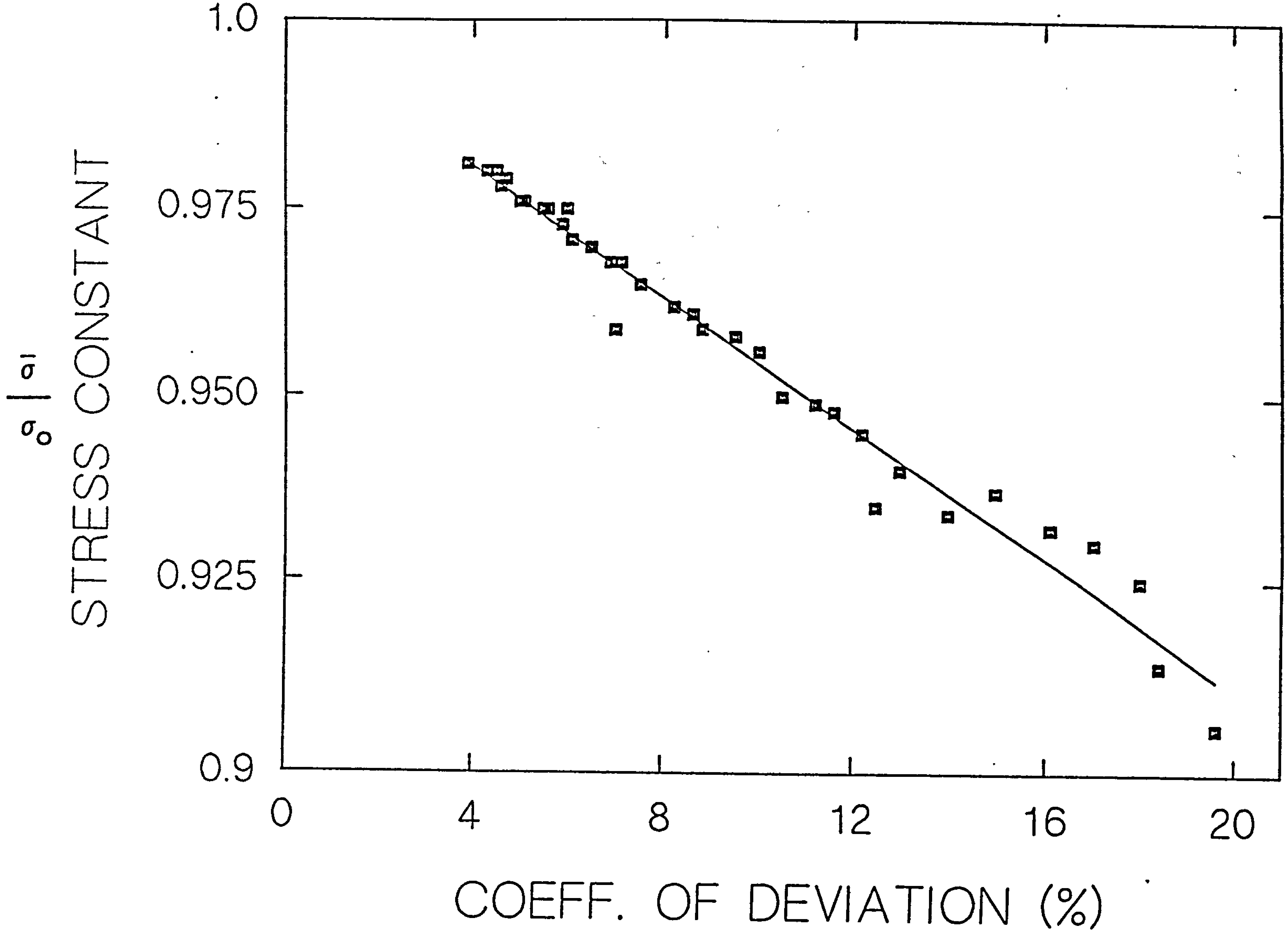


FIGURE 7.2
A relationship between coefficient deviation(%), mean strength and characteristic strength.

CHAPTER EIGHT

The Determination of the Strength Parameters of Brittle Restorative Materials.

8.1 Introduction.

The specimen size and crosshead speed for the compressi test, diametral tensile test and flexural test were selected from the results of the experiments previously described in chapter four, five and six. These results are summarised in the Table 8.1.

Table 8.1 - The test parameters for the mechanical tests.

Mechanical Test	Specimen Size	Crosshead Speed
Compressive Test	Diameter/length Ratio 2:3	0.1 mm per minute
Diametral Tensile Test	Diameter/length Ratio 4:3	0.5 mm per minute
Flexural Test	Span/depth Ratio 5:1 to 10:1	0.5 mm per minute

The specimens of diameter/depth ratio of 2:3 and a crosshead speed of 0.1 mm per minute were found to give a reliable results for the compressive test. Thus specimens of 4 mm diameter by 6 mm in length were chosen for the compressive test. The specimens of diameter/depth ratio 4:3 and crosshead speed of 0.5 mm per minute were found to give the most reliable results for the diametral tensile test. Thus the specimens of 4 mm diameter by 3 mm depth were chosen for the diametral tensile test. Lastly for the flexural test, the specimen of span/depth ratios between 5:1 and 10:1 are found to give the most reliable results when a test crosshead speed of 0.5 mm/min was used. The specimens of span/depth ratio of 10:1 were chosen. A square cross section 2 mm by 2 mm of the rectangular specimens (30 mm in length) were prepared and tested on the base test unit with 20 mm span between support.

One of the aims of this investigation was to determine the strength parameters for the brittle restorative materials used in this study by using the test parameters given in Table 8.1 above. In this investigation the strength parameters from Weibull statistics were compared with the strength parameters of the Normal statistics. The mean strength and standard deviation are the strength parameters of the Normal statistics that have been reported by many workers. Weibull modulus and characteristic strength are the Weibull strength parameters. In addition, the stress at several arbitrary failure probabilities were also calculated and compared for both statistics. The effect of a storage condition on strength parameters on was also studied. The other aim of this investigation was to investigate the reliability of the relationships found in Chapter Seven to predict strength parameter from the mean and standard deviation of a small sample.

8.2 Materials and Methods

Occlusin, Silux and P50 were three the types of light-activated Composite resin. Amalcap and Dispersalloy were the two types of Dental amalgam, and Ketac-Fil and Ketac-Silver were two types of Dental cement used in this study. These materials were subjected to various mechanical tests summarised in the Table 8.2.

Table 8.2 - Materials and designated test.

Mechanical Test	Materials
Compressive Test	Occlusin, Silux, P50, Dispersalloy, Amalcap, Ketac-Fil and Ketac Silver
Diametral Tensile Test	Occlusin, Silux, P50, Dispersalloy, Amalcap, Ketac-Fil and Ketac Silver
Flexural Test	Silux, P50, Dispersalloy, Amalcap, Ketac-Fil and Ketac Silver

Six batches of five specimens were prepared for each test under investigation. The mean strength and deviation coefficient of each batch were calculated. Weibull modulus and characteristic strength of each batch are determined by substituting mean and deviation coefficient (%) in the equations 7.1 and 7.2 (chapter seven). A stress at various levels of failure probabilities for the Weibull statistics, Normal and Student's distributions were predicted. Student's distribution is also used for of the stresses estimated from a smaller sample (Armitage:1971). A computer program was designed to carry out all these calculations. A list of the program is shown in list B of the appendix A. Further more the data of all the batches for each test were cumulatively analysed by another computer program that has been described in chapter four. The list of this program is shown in list A of the appendix A. The strength parameters of this analysis were compared with the strength parameters previously estimated by the analysis of a small sample.

The specimen size and crosshead speed at each type of mechanical test are shown in Table 8.1 For the compressive test, specimens of 4 mm diameter by 6 mm depth were prepared. The specimens were prepared in accordance to the procedure described in chapter three for the compressive test. A crosshead speed of 0.1 mm per minute was used. A total of 60 specimens were prepared for Occlusin, Silux, P50, Amalcap and Dispersalloy. Thirty specimens of six batches of 5 were stored in distilled water in an oven at a constant temperature of 37 ^{o}C and at 100 percent humidity for 7 days prior to testing. The other thirty specimens of six batches of 5 were bench dried for 7 days prior testing. Thirty specimens were prepared for Ketac-fil and Ketac-silver. The specimens were stored in distilled water in an oven of a constant temperature of 37 ^{o}C and 100 percent humidity for 7 days prior to testing. Therefore a grand total of 360 specimens were prepared for the compressive test.

For the diametral tensile test, specimens of 4 mm diameter by 3 mm depth were prepared. The specimens were prepared in accordance to the procedure described in chapter three for the diametral tensile test. A crosshead speed of 0.5 mm per minute was used. Sixty specimens were prepared for Occlusin, Silux, P50, Amalcap and Dispersalloy. Thirty specimens of six batches of 5 were stored in distilled water and in an oven at a constant temperature of 37 ^{o}C and 100 percent humidity, for 7 days prior testing. The other thirty specimens of six batches of 5 were bench dried for 7 days prior testing. Thirty specimens were prepared for Ketac-fil and Ketac-silver. and stored in distilled water in an oven of a constant temperature of 37 ^{o}C and 100 percent humidity for 7 days prior to testing. Hence, a grand total of 360 specimens were prepared for the diametral tensile test.

A square cross section 2 mm by 2 mm of the rectangular specimens (30 mm in length) were prepared for the flexural test. The specimens were prepared in accordance to the procedure described in chapter three for the flexural test. The specimens were tested on the base test unit with 20 mm span between support. A crosshead speed of 0.5 mm per minute was used. Sixty specimens were prepared for Silux, P50, Amalcap and Dispersalloy. Thirty specimens of six batches of 5 were stored in distilled water in an oven of a constant temperature of 37 ^{o}C and 100 percent humidity for 7 days prior to testing. The other thirty specimens of six batches of 5 were bench dried for 7 days prior to testing. Thirty specimens were prepared for Ketac-fil and Ketac-silver. The specimens were stored in distilled water in an oven of a constant temperature of 37 ^{o}C and 100 percent humidity for 7 days prior to testing. Therefore a grand total of 300 specimens were prepared for the flexural test.

8.3 Results and Discussion.

Before any strength parameters can be estimated, one must decide at what crosshead speed the test shall be carried out. Not only that, one must also decide which size of specimen shall be used. Furthermore how many specimen shall be prepared. The results from Chapters Four, Five and Six have shown that the crosshead speed and specimen size affect the mechanical strength of the brittle materials. A crosshead speed of 0.1 mm per minute is recommended for the compressive testing of brittle materials. A crosshead speed of 0.5 mm per minute is recommended for the diametral tensile test and flexural test. The specimen size of 4 mm diameter by 6 mm length was chosen for the compressive test specimen. A specimen size of 4 mm diameter by 3 mm length was chosen for the diametral tensile test specimen. Lastly a specimen size of a span/depth ratio of 10:1 was chosen for flexural test specimen. A rectangular specimen of 2 mm by 2 mm cross section by 25 mm length and span of 20 mm was used.

Each group of 30 specimens was first analysed by both Weibull and Normal analysis. Then the mean and the percentage of deviation coefficient for each batch were calculated. As a result, the Weibull modulus and it's characteristic strength could be estimated. Based on these parameters, the stress at any probability of failure could be predicted.

The summary of the Weibull and Normal analysis for 'wet' and 'dry' storage conditions are shown in a Tables with letter 'a' in the bracket (example Table 8.3.1(a)). The Tables also show the stress predicted by both Weibull and Normal analysis at several levels of probability of failure. The Tables with letter 'b' in the bracket show the raw data of each batch. The mean strength and deviation coefficient(%) were calculated for each batch. The estimated value of Weibull modulus and characteristic strength are also shown. Weibull modulus and characteristic strength were estimated by using the mean strength and the percentage of deviation coefficient.

Figures with letter 'a' in the bracket show a graphical illustration of the Weibull statistics. Each Figure shows the Weibull curve for each material stored in 'wet' and 'dry' storage, except for the flexural test of dental cements since only 'wet' specimens were prepared. The estimated stress at various levels of failure probability for each batch was reported as a bar chart. Figures with letter 'b' in the bracket show the bar charts for the estimated stress at 0.01, 0.1, 1 and 99.99 percent failure probabilities for the 'wet' specimens. The estimated stress at various levels of failure probability for the 'dry' specimens are shown in Figures with letter 'c' in the bracket. The bar chart for any predicted stress is not shown when the value falls below zero.

8.3.1 Compressive Test of Light Activated Composite Resin.

The results for the compressive test of Occlusin are shown in Tables 8.3.1.1(a) and 8.3.1.1(b), and Figures 8.3.1.1(a), 8.3.1.1(b) and 8.3.1.1(c). The results for the compressive test of Opalux are shown in Tables 8.3.1.2(a) and 8.3.1.2(b), and Figures 8.3.1.2(a), 8.3.1.2(b) and 8.3.1.2(c). The results for the compressive test of occlusin are shown in Tables 8.3.1.3(a) and 8.3.1.3(b), and Figures 8.3.1.3(a), 8.3.1.3(b) and 8.3.1.3(c).

The specimens for the compressive strength of Occlusin were tested at a crosshead speed of 0.1 mm per minute. The test of the specimens stored in distilled water at 37^{o} C for 7 days prior testing was termed 'wet storage'. The test of the bench dried specimens for 7 days prior testing was termed as 'dry storage'.

TABLE 8.3.1.1(a)

Summary of Weibull analysis-Compressive strength of Occlusin for the specimens of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1mm/min.

Conditions		Wet	Dry
Weibull Modulus		25.4	18.3
Characteristic Strength^{+}		232.4	223.5
Standard Error of Modulus		0.79	0.9
Coeff. of Correlation		0.98	0.94
Mean Strength^{+}		227.7	217.6
Deviation Coefficient (%)		4.28	5.57
Estimated Stress^{+} at Failure Probability			
0.01%	- Weibull	161.7	135.1
	Normal	221.1	209.4
1%	- Weibull	193.9	173.8
	Normal	223.6	212.4
99.99%	- Weibull	246.8	242.9
	Normal	234.3	225.8

+ Unit in Mpa.

Oneway analysis of variance-Very highly significant difference between strength of the specimens stored in wet condition compared with the strength of the specimens stored in dry condition (P<0.001).

TABLE 8.3.1.1(b)

(i) Wet Compressive strength of Occlusin. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5	6
Data 1+	234.9	232.9	232.9	234.9	220.9	234.9
Data 2+	228.9	222.9	215.0	236.9	211.0	240.8
Data 3+	207.0	236.9	217.0	222.9	238.9	238.9
Data 4+	234.9	218.9	213.0	232.9	228.9	215.0
Data 5+	224.9	222.9	236.9	228.9	221.7	244.8
Mean Strength+	226.1	226.9	222.9	231.3	224.3	234.9
Deviation Coefficient (%)	4.5	3.0	4.4	2.1	4.1	4.5
Weibull Modulus	23.8	36.5	24.3	51.6	26.2	24.3
Characteristic Strength+	231.1	230.3	227.8	233.9	228.8	240.0

(ii) Dry Compressive strength of Occlusin. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5
Data 1+	246.8	217.0	209.0	207.0	232.9
Data 2+	201.0	211.0	234.9	191.1	211.0
Data 3+	215.0	228.9	228.9	201.0	207.0
Data 4+	201.0	226.9	222.9	218.9	201.0
Data 5+	226.9	211.0	226.9	220.9	205.0
Mean Strength+	218.2	218.9	224.6	207.8	211.4
Deviation Coefficient (%)	7.9	3.5	3.9	5.4	5.3
Weibull Modulus	13.4	31.1	28.1	20.0	20.3
Characteristic Strength+	226.4	222.7	228.8	213.2	216.8

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34°C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

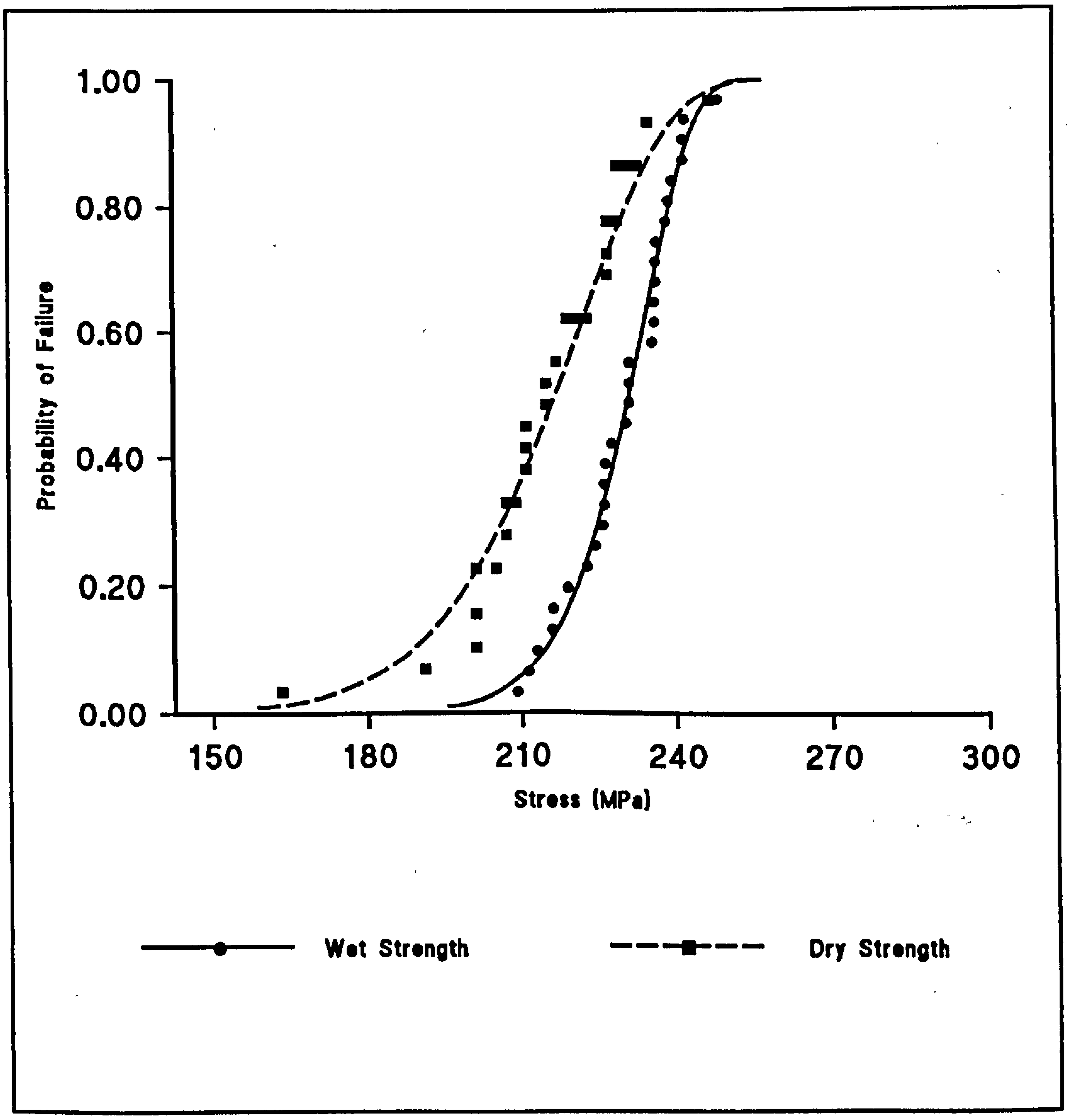


FIGURE 8.3.1.1(a)
Compressive strength of Occlusin-Probability of failure versus compressive stress for the specimens of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1mm/min.

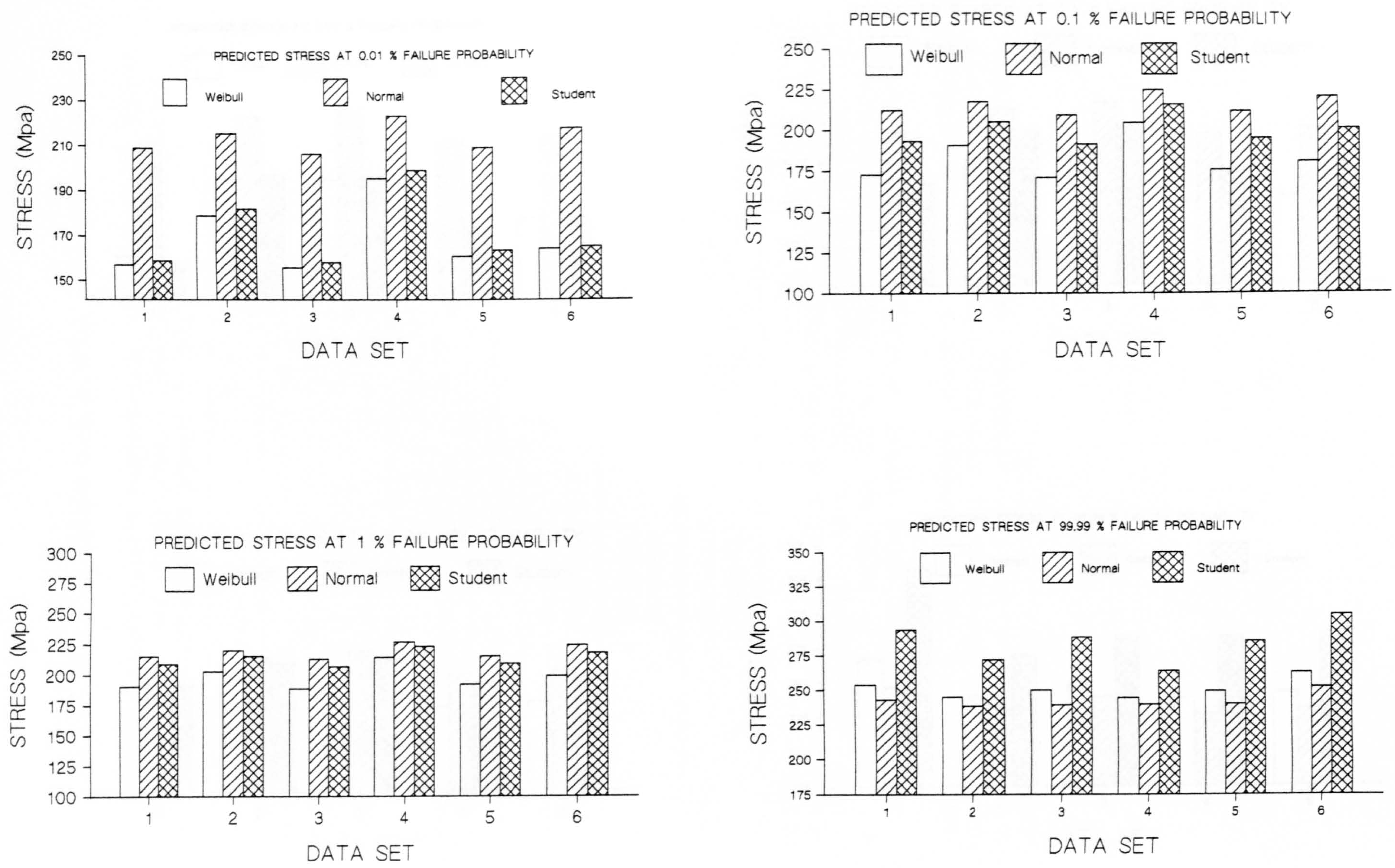


FIGURE 8.3.1.1(b) - Wet Compressive strength of Occlusin. Predicted stress at various failure probability levels.

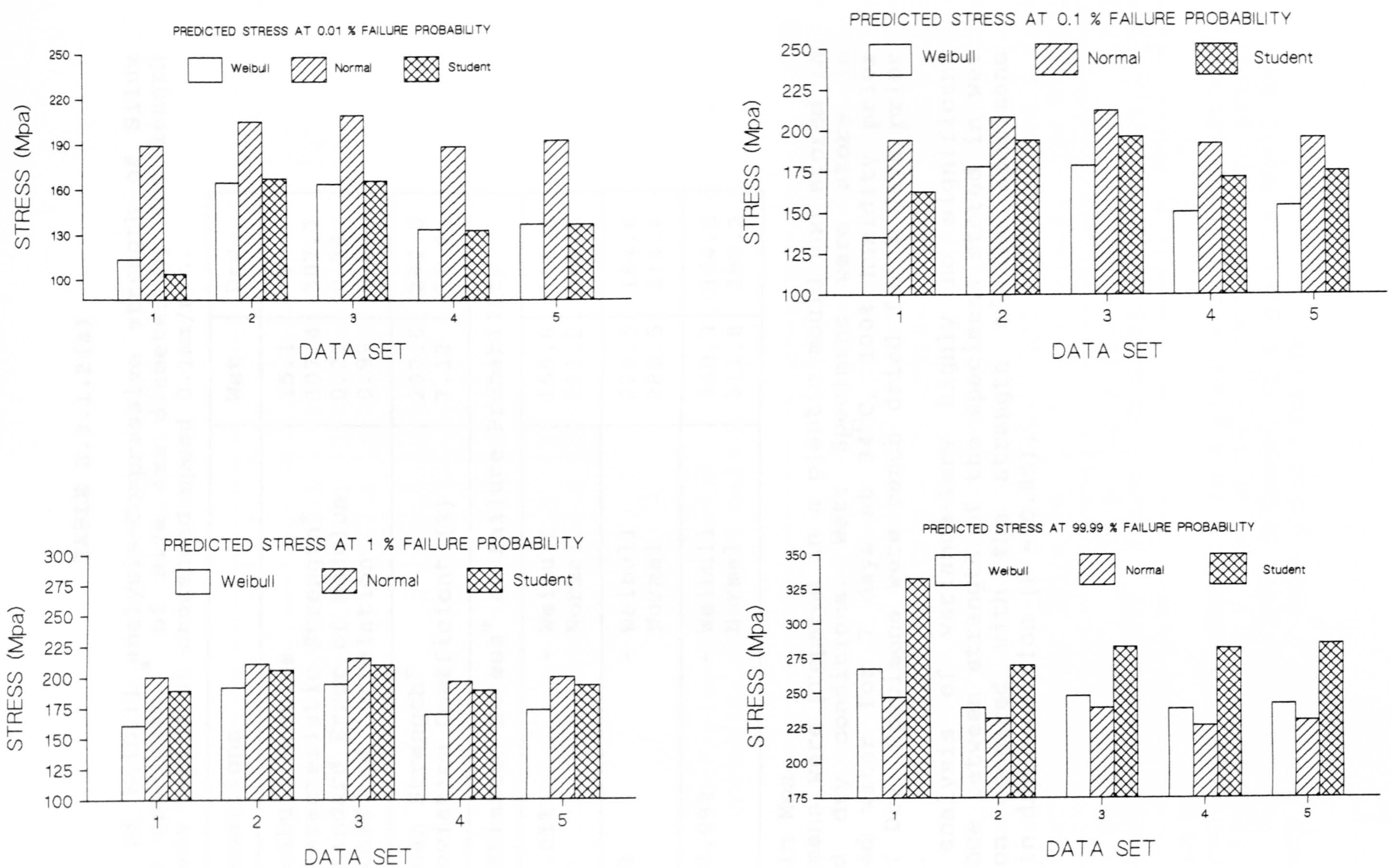


FIGURE 8.3.1.1(c) - Dry Compressive strength of Occlusin. Predicted stress at various failure probability levels.

TABLE 8.3.1.2(a)

Summary of Weibull analysis-Compressive strength of Silux for the specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1mm/min.

Conditions		Wet	Dry
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation		15.1 307.4 0.29 0.99	9 307.7 0.34 0.96
Mean Strength+ Deviation Coefficient (%)		297.5 7.12	292.0 11.4
Estimated Stress+ at Failure Probability			
0.01%	- Weibull Normal	166.8 283.2	110.0 168.8
1%	- Weibull Normal	226.5 288.5	184.6 214.4
99.99%	- Weibull Normal	340.3 311.8	364.6 395.2

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at 34°C, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.
Oneway analysis of variance-Very highly no significant difference between strength of the specimens stored in wet condition compared with the strength of the specimens stored in dry condition (P = 0.85).

TABLE 8.3.1.2(b)

(i) Wet Compressive strength of Silux. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5	6
Data+1	296.1	308.3	280.1	321.7	173.2	303.6
Data+2	300.1	307.1	180.0	318.5	173.2	315.2
Data+3	287.5	287.2	275.7	268.1	307.6	324.3
Data+4	286.8	292.1	262.1	312.9	290.1	327.0
Data+5	320.1	275.5	335.8	279.5	303.6	246.8
Mean Strength+	298.1	294.0	266.7	300.1	249.5	303.4
Deviation Coefficient (%)	4.05	4.22	18.8	7.33	25.09	9.7
Weibull Modulus	26.7	25.6	5.52	14.5	4.1	10.9
Characteristic Strength+	304.0	300.1	291.2	310.6	280.9	317.4

(ii) Dry Compressive strength of Silux. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5	6
Data 1+	286.9	300.6	248.2	315.6	198.0	300.1
Data 2+	319.3	292.4	213.0	326.1	278.7	295.0
Data 3+	283.4	237.2	269.4	288.4	206.0	357.7
Data 4+	296.0	301.1	332.1	301.6	245.7	293.9
Data 5+	293.0	302.1	314.3	320.9	202.1	224.3
Mean Strength+	295.7	286.7	275.4	310.5	226.1	294.2
Deviation Coefficient (%)	4.26	8.71	15.74	4.43	13.87	14.4
Weibull Modulus	25.4	12.2	6.6	24.4	7.5	7.3
Characteristic Strength+	301.9	298.6	296.4	317.2	241.2	314.7

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34^{o}C , 100% humidity prior testing. Dry secimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

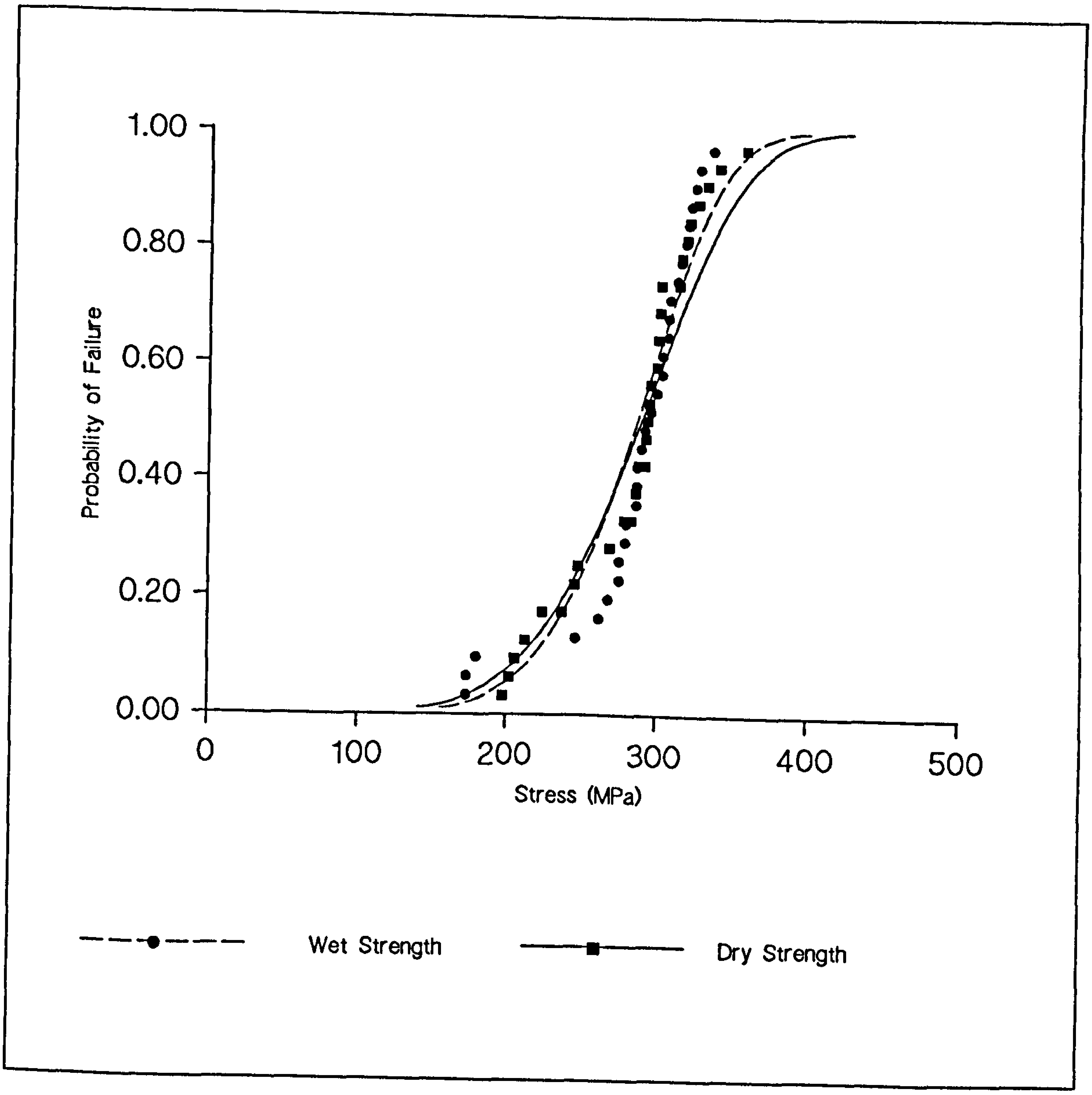


FIGURE 8.3.1.2(a)
Compressive strength of Silux-Probability of failure versus compressive stress for the specimens of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1mm/min.

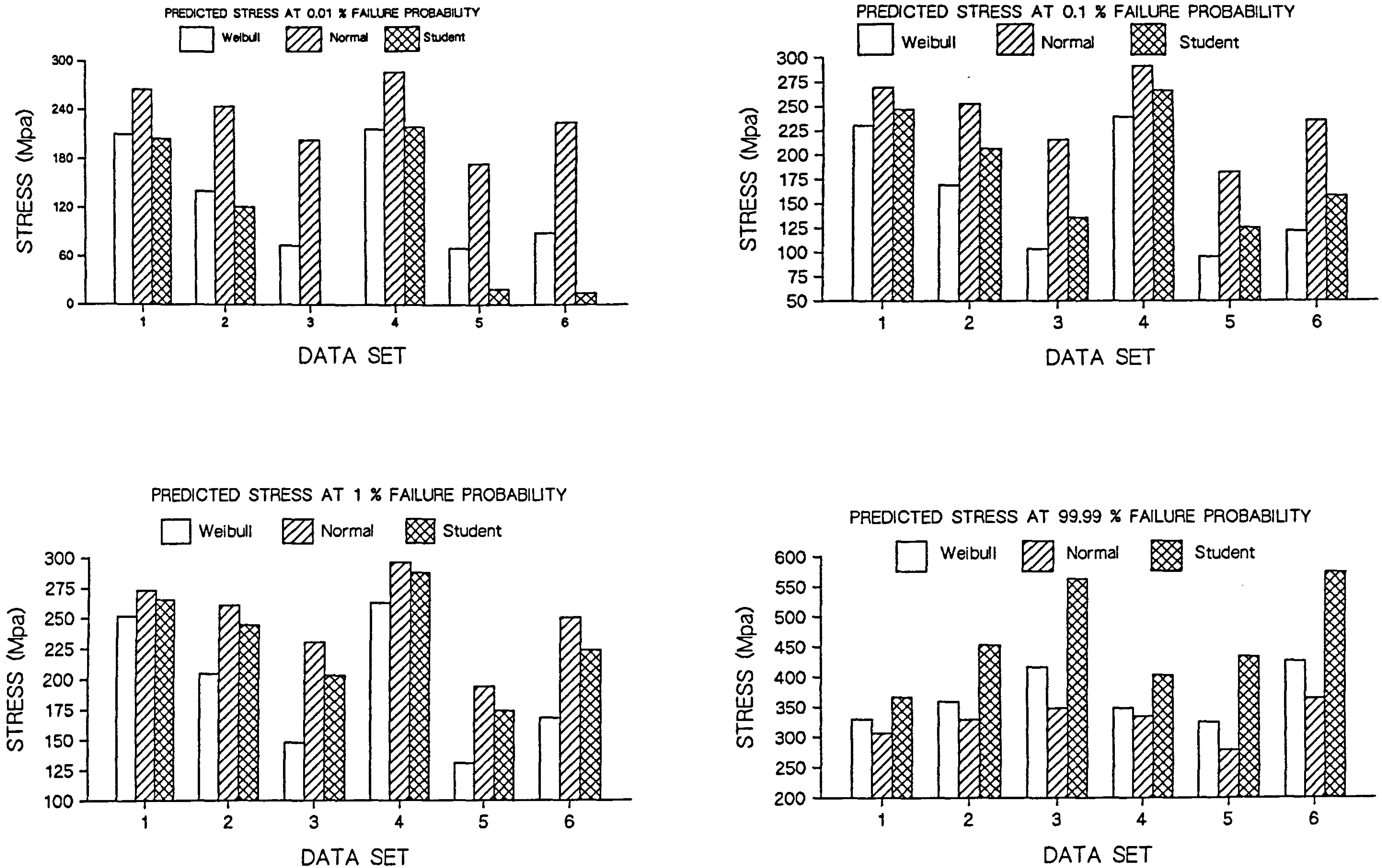


FIGURE 8.3.1.2(b) - Wet Compressive strength of Silux. Predicted stress at various failure probability levels.

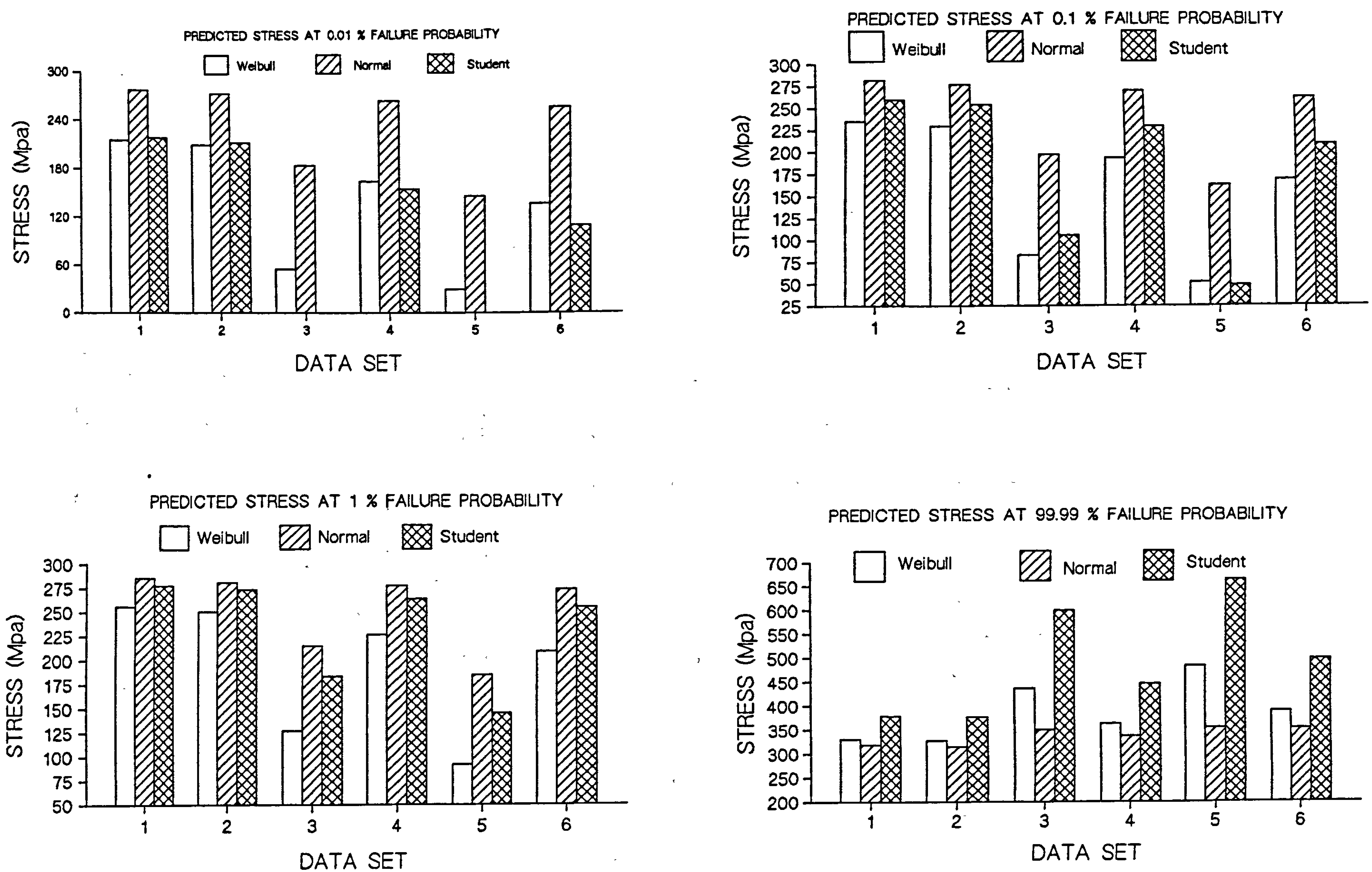


FIGURE 8.3.1.2(c) - Dry Compressive strength of Silux. Predicted stress at various failure probability levels.

TABLE 8.3.1.3(a)

Summary of Weibull analysis-Compressive strength of P50 Plus for the specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1mm/min.

Conditions		Wet	Dry
Weibull Modulus		12.2	11.6
Characteristic Strength+		349.2	353.0
Standard Error of Modulus		0.35	0.51
Coeff. of Correlation		0.98	0.96
Mean Strength+		335.4	338.6
Deviation Coefficient (%)		8.62	8.82
Estimated Stress+ at Failure Probability			
0.01%	- Weibull	164.2	159.5
	Normal	315.9	318.4
1%	- Weibull	239.5	237.4
	Normal	323.1	325.9
99.99%	- Weibull	395.8	402.7
	Normal	354.9	358.8

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at 34°C, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.

Oneway analysis of variance-Very highly no significant difference between strength of the specimens stored in wet condition compared with the strength of the specimens stored in dry condition (P = 0.6).

TABLE 8.3.1.3(b)

(i) Wet Compressive strength of P50. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5
Data+1	384.1	357.2	339.5	345.2	337.1
Data+2	341.2	341.5	295.8	311.2	335.9
Data+3	351.3	325.7	268.8	299.6	328.5
Data+4	369.6	353.4	367.6	339.2	380.7
Data+5	363.7	355.4	304.6	315.2	318.8
Mean Strength+	362.0	346.6	315.2	322.1	340.2
Deviation Coefficient (%)	4.09	3.41	10.97	5.38	6.25
Weibull Modulus	26.5	31.9	9.6	20.0	17.1
Characteristic Strength+	369.2	352.5	331.8	330.4	350.4

(ii) Dry Compressive strength of P50. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5
Data+1	359.7	353.4	228.6	351.6	306.2
Data+2	371.9	359.9	341.2	386.9	297.6
Data+3	273.4	329.0	285.5	309.9	343.8
Data+4	353.4	359.7	224.1	356.5	359.7
Data+5	272.1	340.1	332.1	364.1	371.8
Mean Strength+	326.1	348.4	282.3	353.8	335.8
Deviation Coefficient (%)	13.48	3.47	17.52	7.08	8.7
Weibull Modulus	7.76	31.4	5.9	15.1	12.2
Characteristic Strength+	347.2	354.4	306.4	365.8	349.8

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34°C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

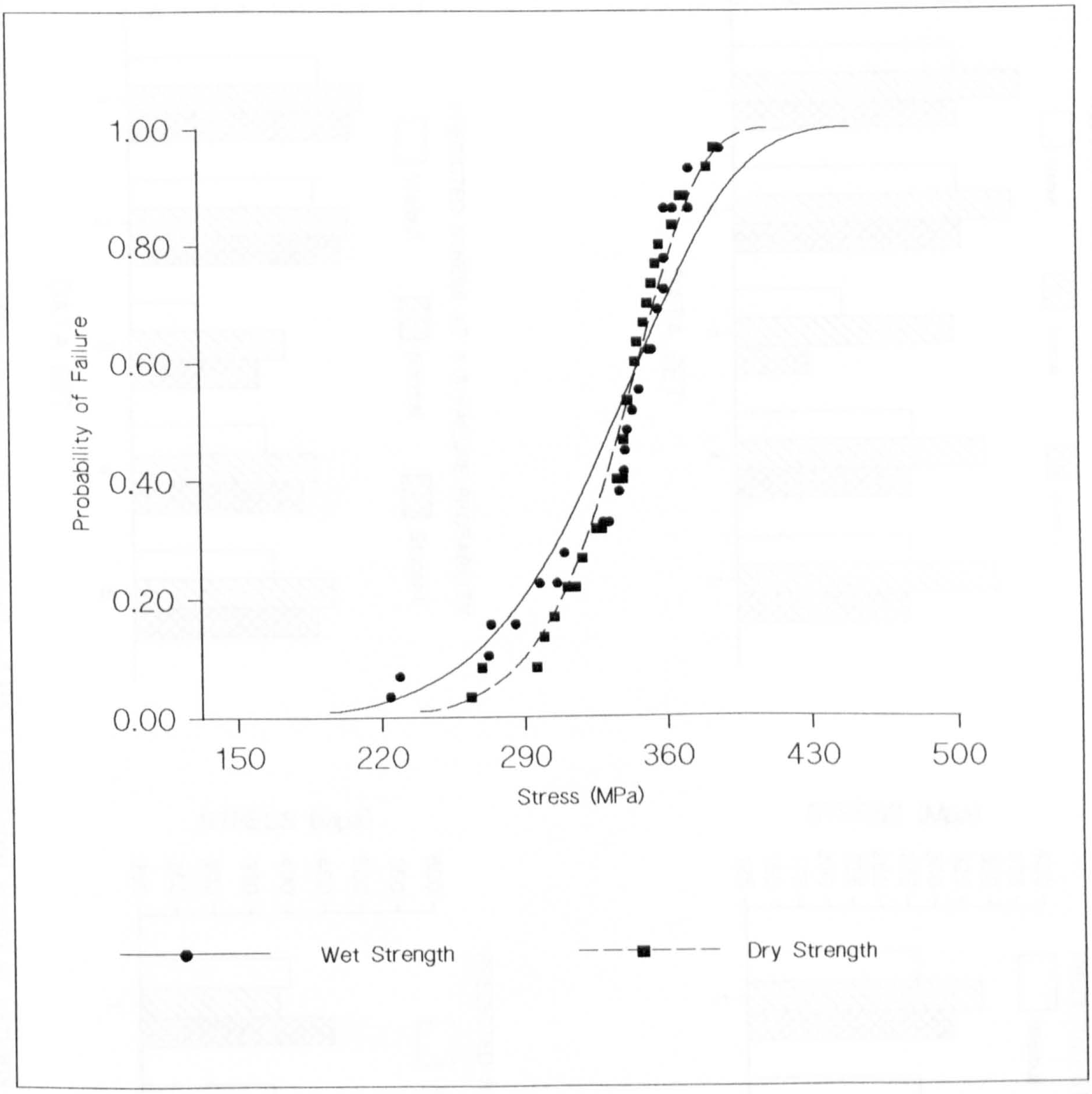
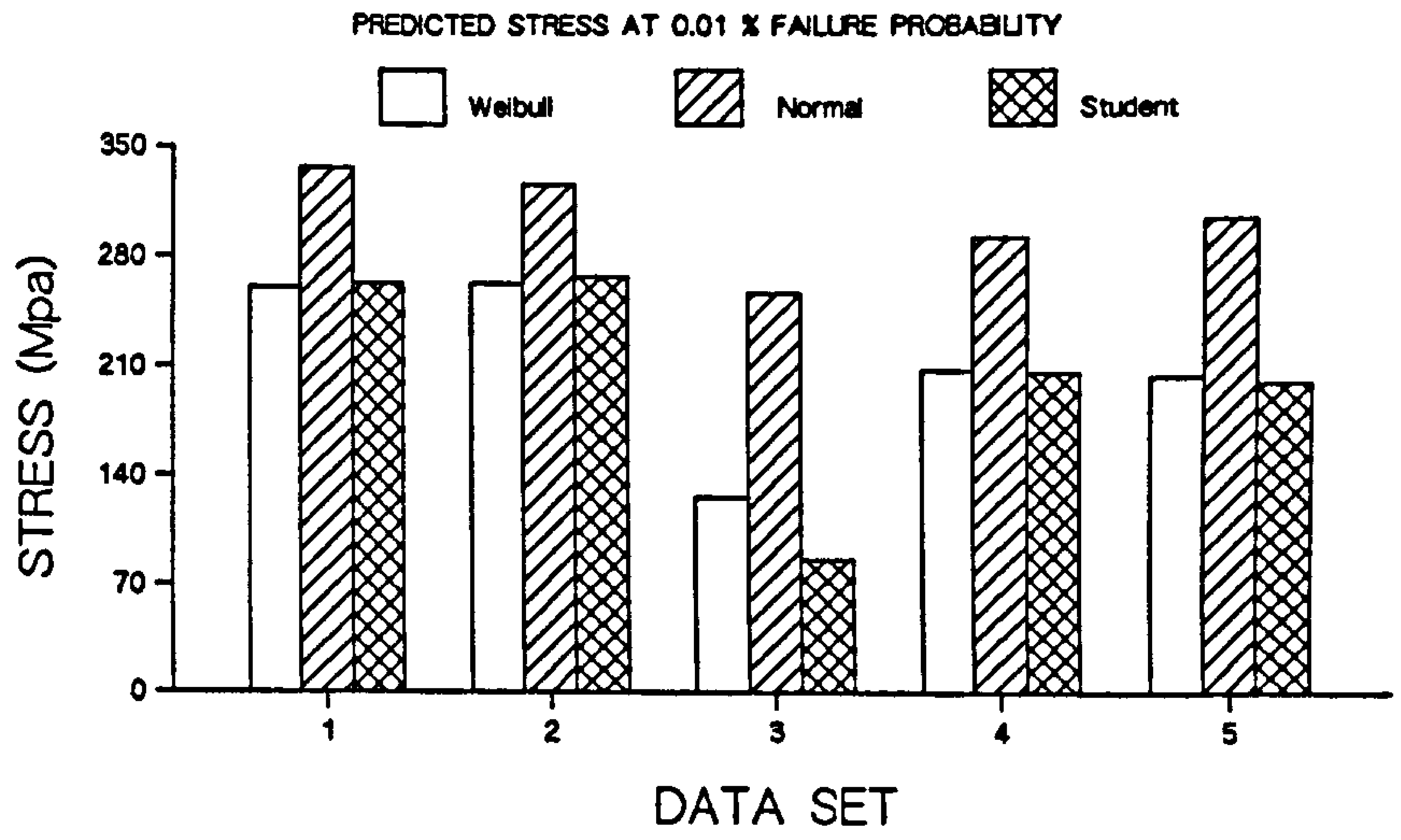
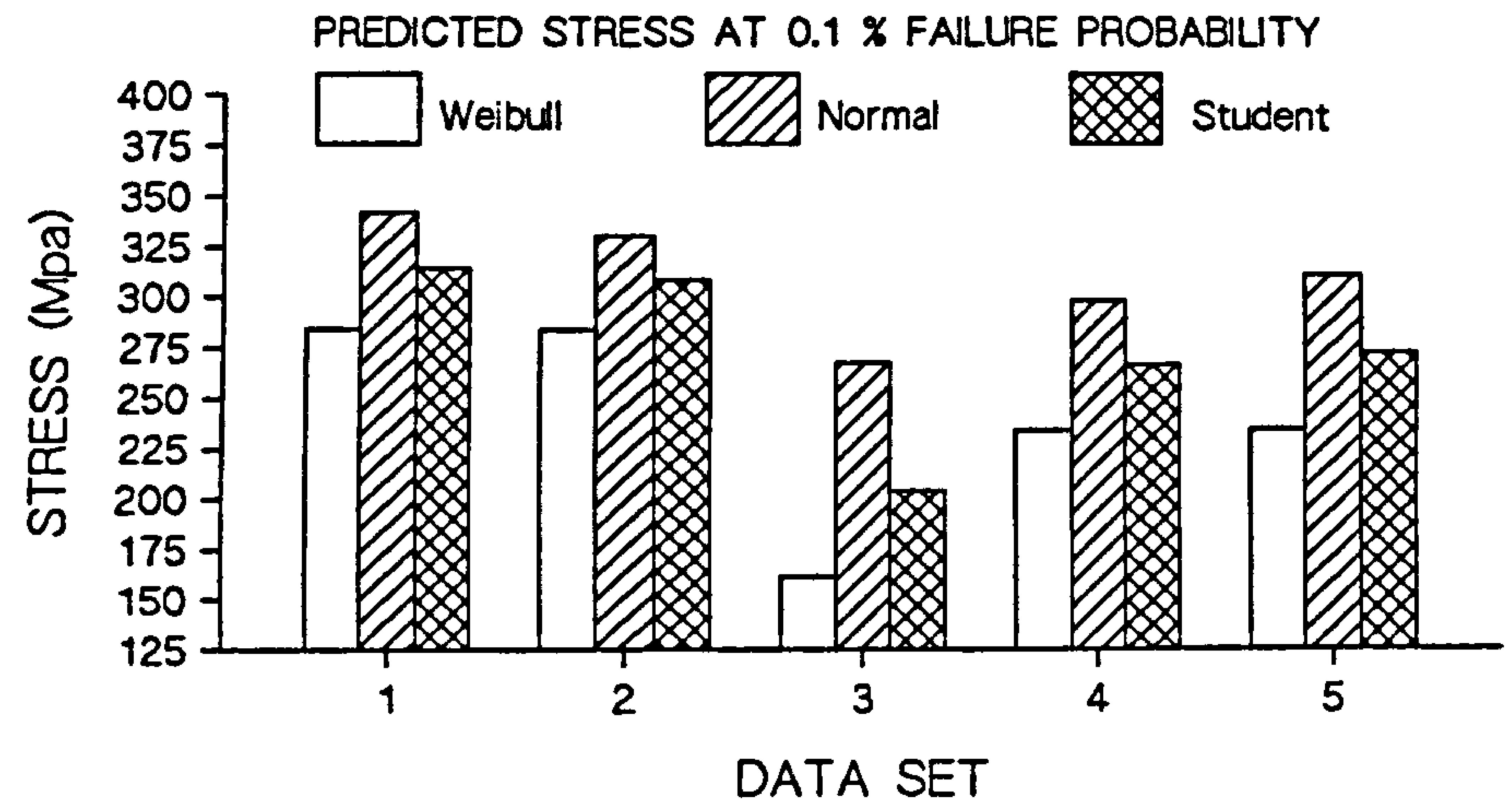
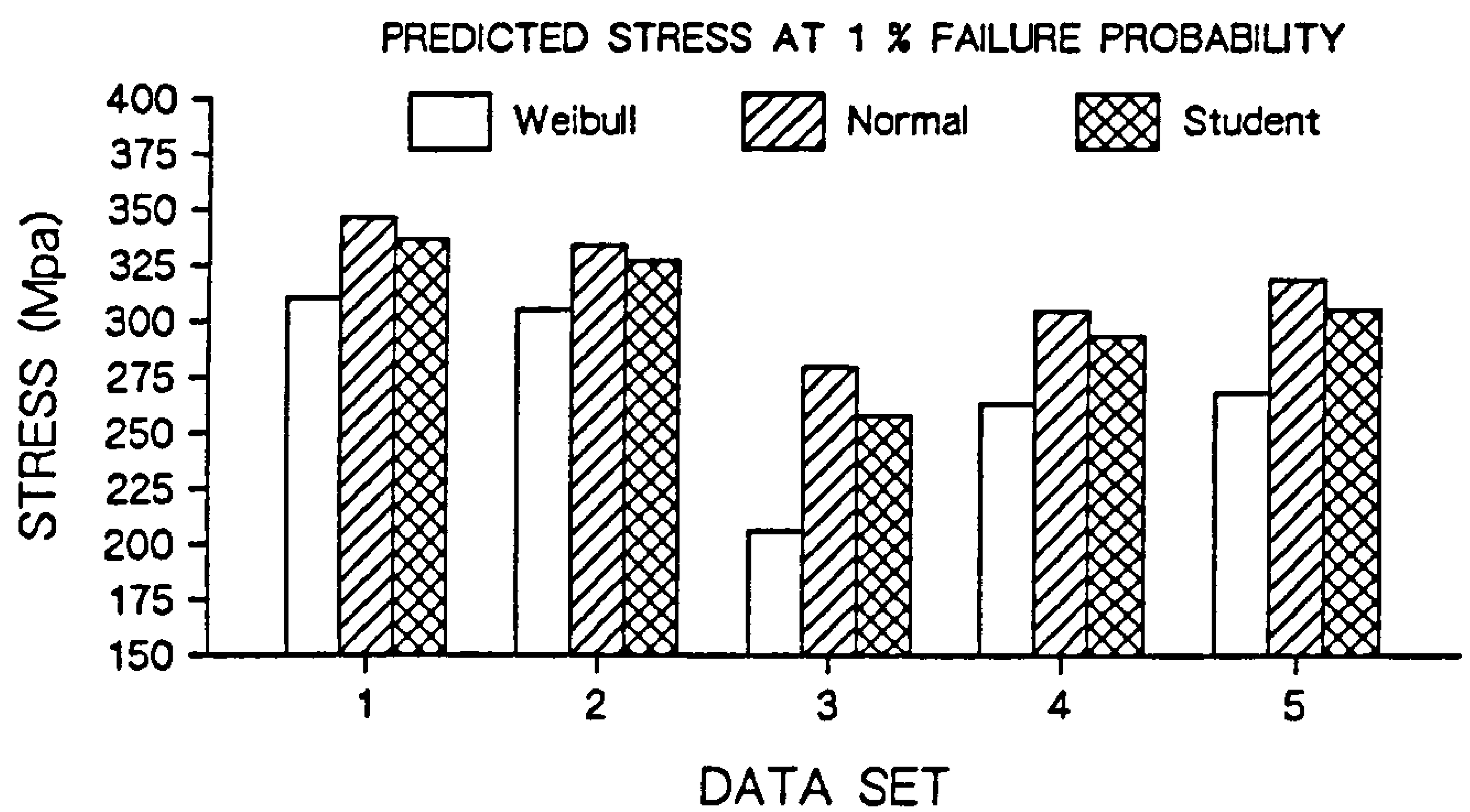


FIGURE 8.3.1.3(a)
Compressive strength of P50 Plus-Probability of failure versus compressive stress for the specimens of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1mm/min.







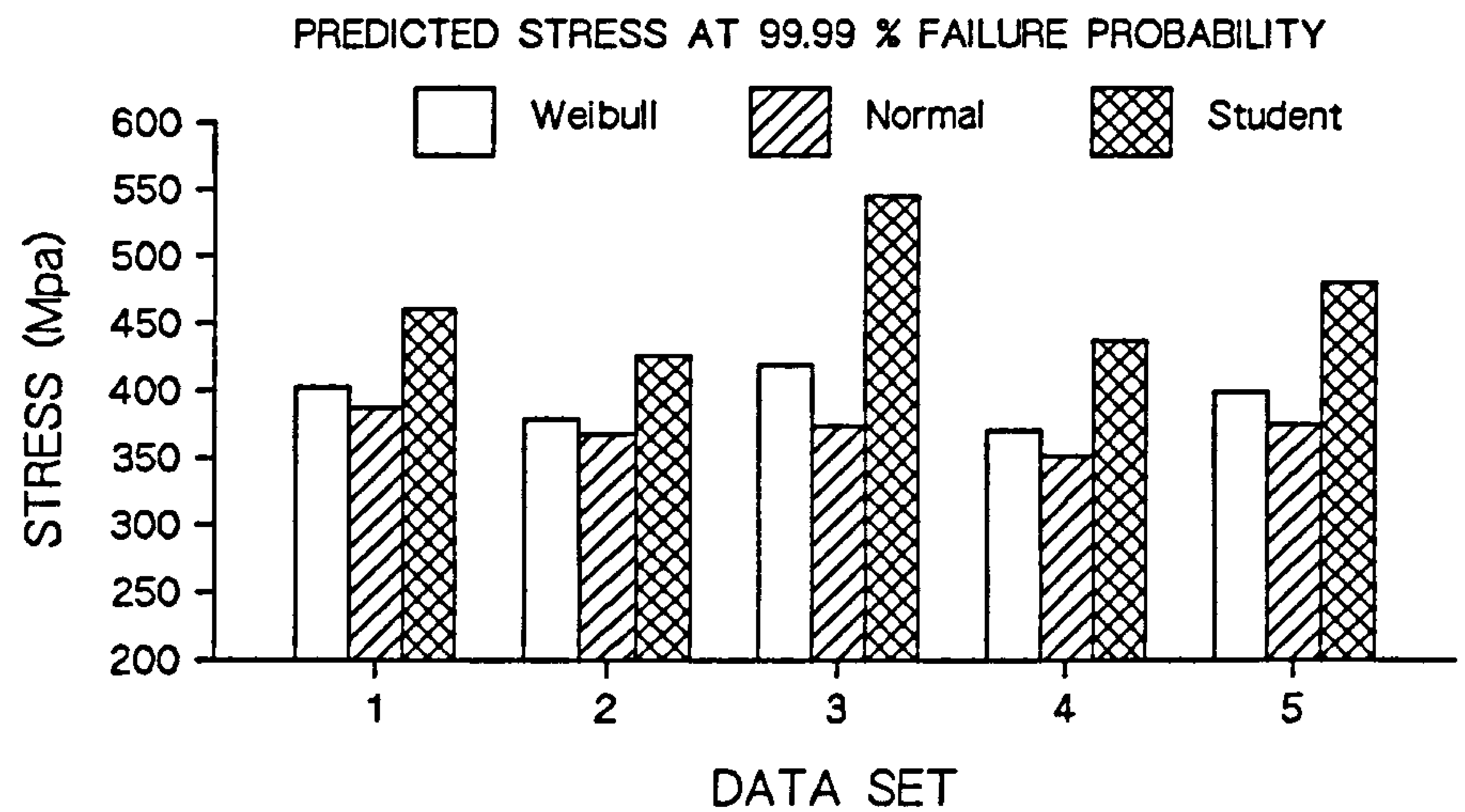


FIGURE 8.3.1.3(b) - Wet Compressive strength of P50. Predicted stress at various failure probability levels.

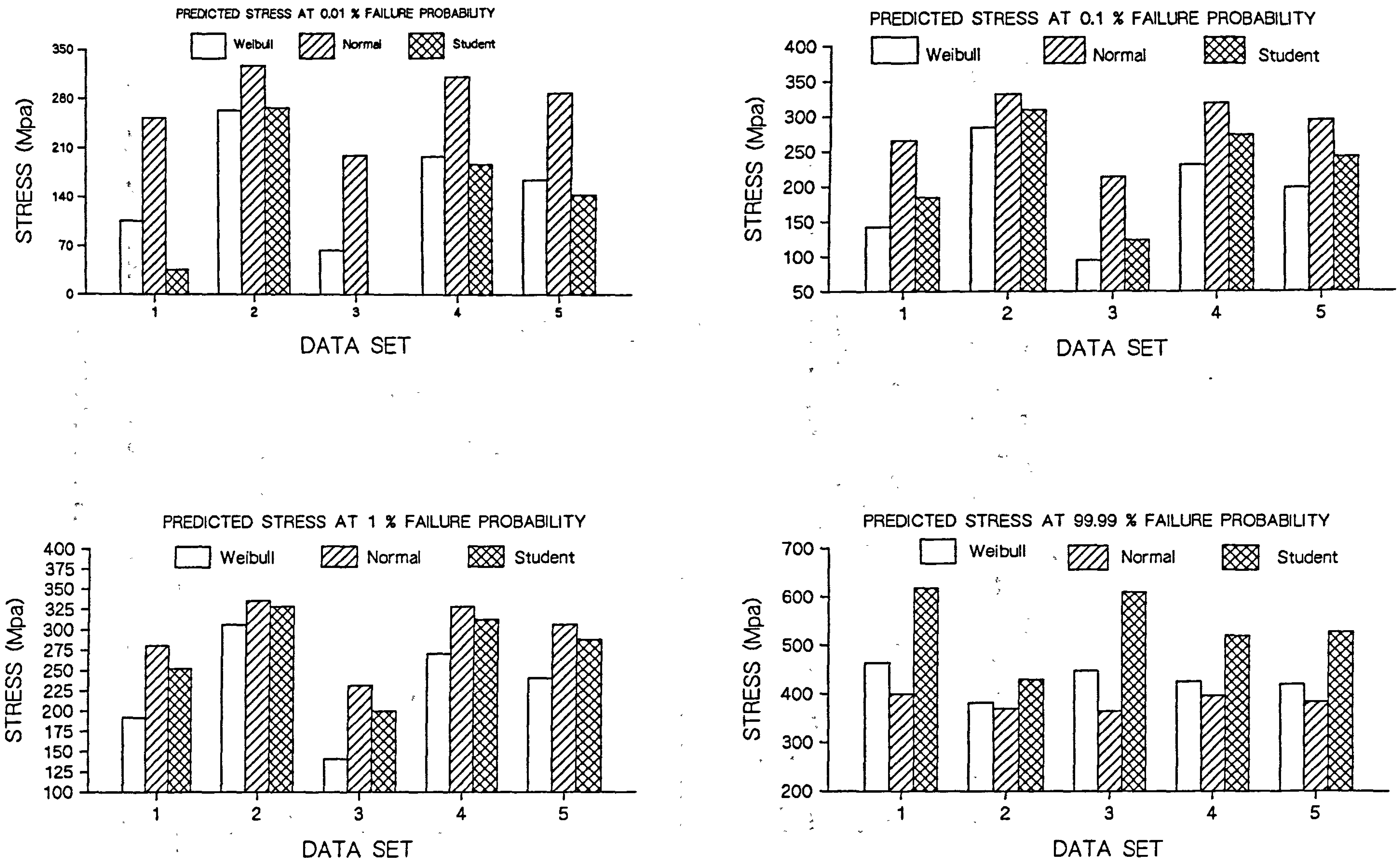


FIGURE 8.3.1.3(c) -Dry Compressive strength of P50. Predicted stress at various failure probability levels.

TABLE 8.3.2.1(a)

Summary of Weibull analysis-Compressive strength of Amalcap for the specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1mm/min.

Conditions		Wet	Dry
Weibull Modulus		23.2	19.3
Characteristic Strength+		410.6	379.3
Standard Error of Modulus		0.58	0.64
Coeff. of Correlation		0.98	0.97
Mean Strength+		401.7	369.5
Deviation Coefficient (%)		4.65	5.57
Estimated Stress+ at Failure Probability			
0.01%	- Weibull	276.0	235.1
	Normal	389.1	355.6
1%	- Weibull	336.7	298.7
	Normal	393.8	360.7
99.99%	- Weibull	438.5	410.6
	Normal	414.3	383.4

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at 34°C, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.

Oneway analysis of variance-Very highly significant difference between the strength of the specimens stored in a wet condition compared with the strength of the specimens stored in dry condition (P<0.001).

TABLE 8.3.2.1(b)

(i) Wet Compressive strength of Amalcap. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5
Data+1	296.6	378.2	374.2	408.0	370.3
Data+2	418.0	420.0	408.0	414.0	404.1
Data+3	426.0	429.9	302.6	424.0	400.1
Data+4	422.0	394.1	420.0	398.1	422.0
Data+5	386.2	390.1	398.1	398.1	378.2
Mean Strength+	389.7	402.5	380.6	408.4	394.9
Deviation Coefficient (%)	12.5	4.81	11.0	2.42	4.71
Weibull Modulus	8.4	22.4	9.6	45.5	22.9
Characteristic Strength+	413.1	411.9	400.6	413.5	404.0

(ii) Dry Compressive strength of Amalcap. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5	6
Data+1	330.3	352.1	370.0	366.1	386.0	346.2
Data+2	384.0	390.0	393.9	372.0	382.0	366.1
Data+3	318.3	395.9	370.0	362.1	268.1	330.3
Data+4	382.0	376.0	376.0	328.3	382.0	366.1
Data+5	374.0	344.2	389.9	395.9	372.0	360.1
Mean Strength+	357.7	371.6	380.0	364.9	378.0	353.7
Deviation Coefficient (%)	7.76	5.48	2.65	5.96	1.79	3.9
Weibull Modulus	13.7	19.6	41.4	18.0	61.8	27.8
Characteristic Strength+	371.0	381.5	385.1	375.3	381.7	360.5

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34^{o}C , 100% humidity prior testing. D specimens were prepared in a plastic mould and were bench dried for days prior testing.

TABLE 8.3.2.1(b)

(i) Wet Compressive strength of Amalcap. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5
Data+1	296.6	378.2	374.2	408.0	370.3
Data+2	418.0	420.0	408.0	414.0	404.1
Data+3	426.0	429.9	302.6	424.0	400.1
Data+4	422.0	394.1	420.0	398.1	422.0
Data+5	386.2	390.1	398.1	398.1	378.2
Mean Strength+	389.7	402.5	380.6	408.4	394.9
Deviation Coefficient (%)	12.5	4.81	11.0	2.42	4.71
Weibull Modulus	8.4	22.4	9.6	45.5	22.9
Characteristic Strength+	413.1	411.9	400.6	413.5	404.0

(ii) Dry Compressive strength of Amalcap. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5	6
Data+1	330.3	352.1	370.0	366.1	386.0	346.2
Data+2	384.0	390.0	393.9	372.0	382.0	366.1
Data+3	318.3	395.9	370.0	362.1	268.1	330.3
Data+4	382.0	376.0	376.0	328.3	382.0	366.1
Data+5	374.0	344.2	389.9	395.9	372.0	360.1
Mean Strength+	357.7	371.6	380.0	364.9	378.0	353.7
Deviation Coefficient (%)	7.76	5.48	2.65	5.96	1.79	3.9
Weibull Modulus	13.7	19.6	41.4	18.0	61.8	27.8
Characteristic Strength+	371.0	381.5	385.1	375.3	381.7	360.5

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34°C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

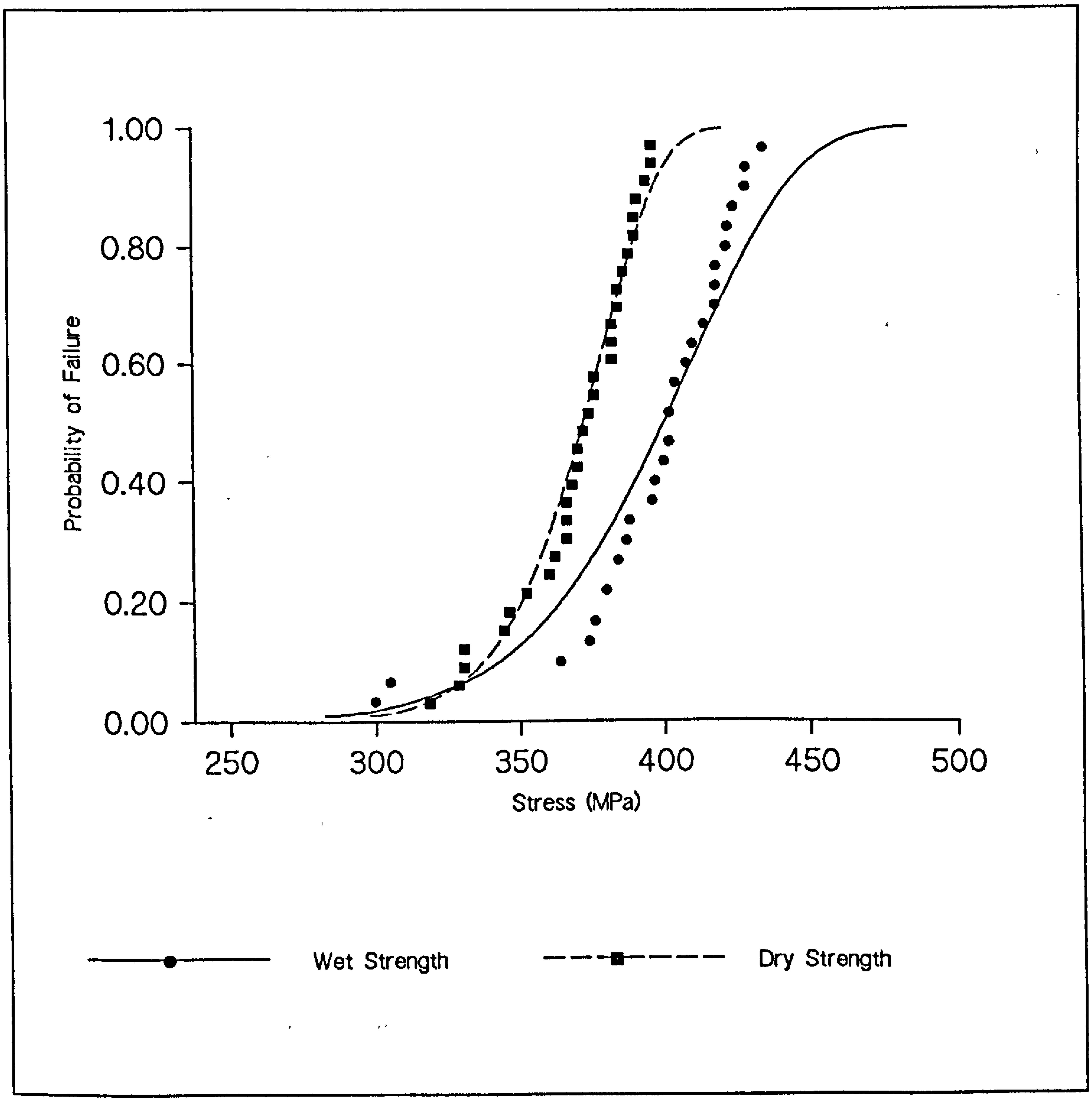


FIGURE 8.3.2.1(a)
Compressive strength of Amalcap-Probability of failure versus compressive stress for the specimens of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1mm/min.

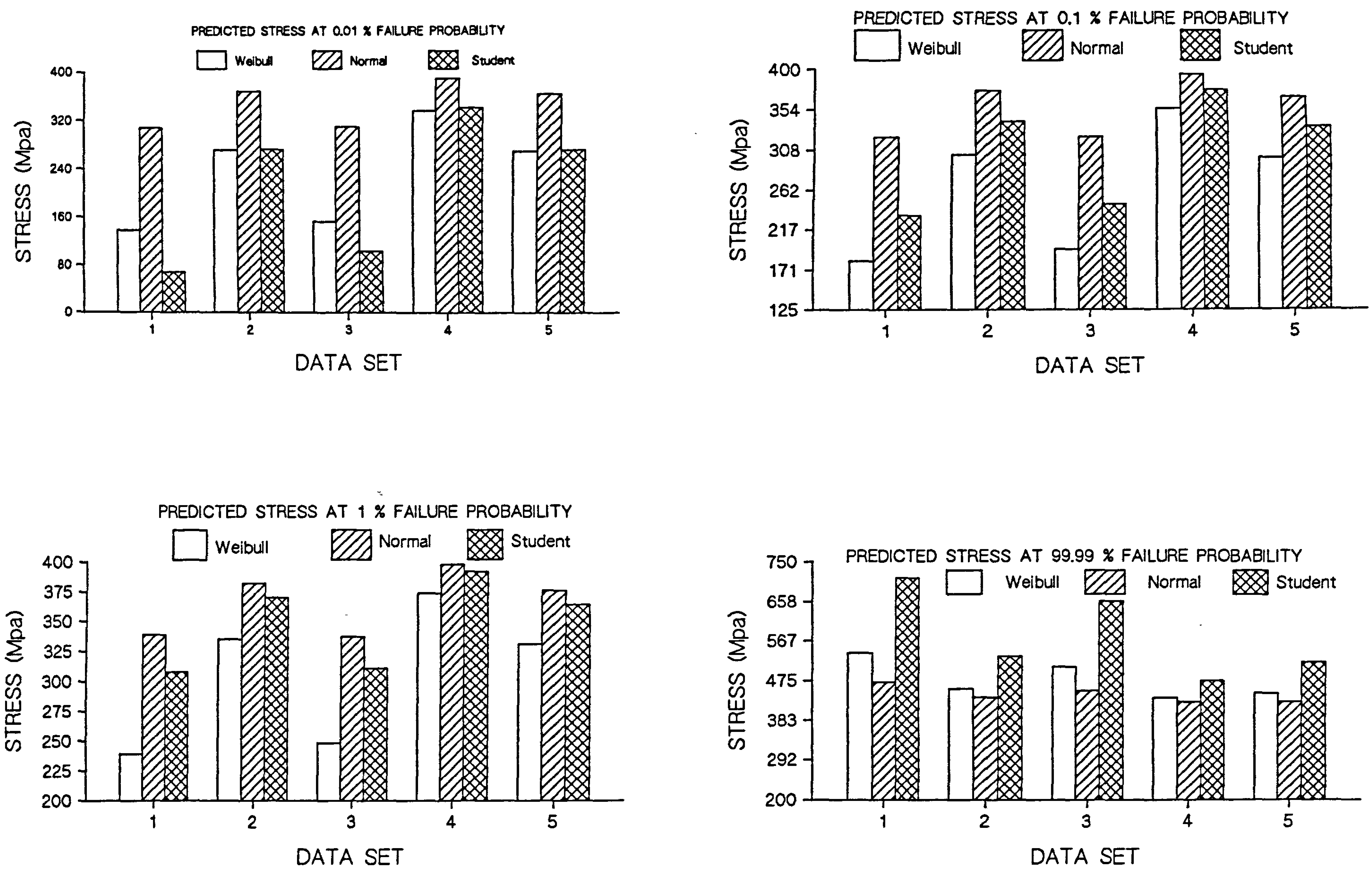


FIGURE 8.3.2.1(b) - Wet Compressive strength of Amalcap. Predicted stress at various failure probability levels.

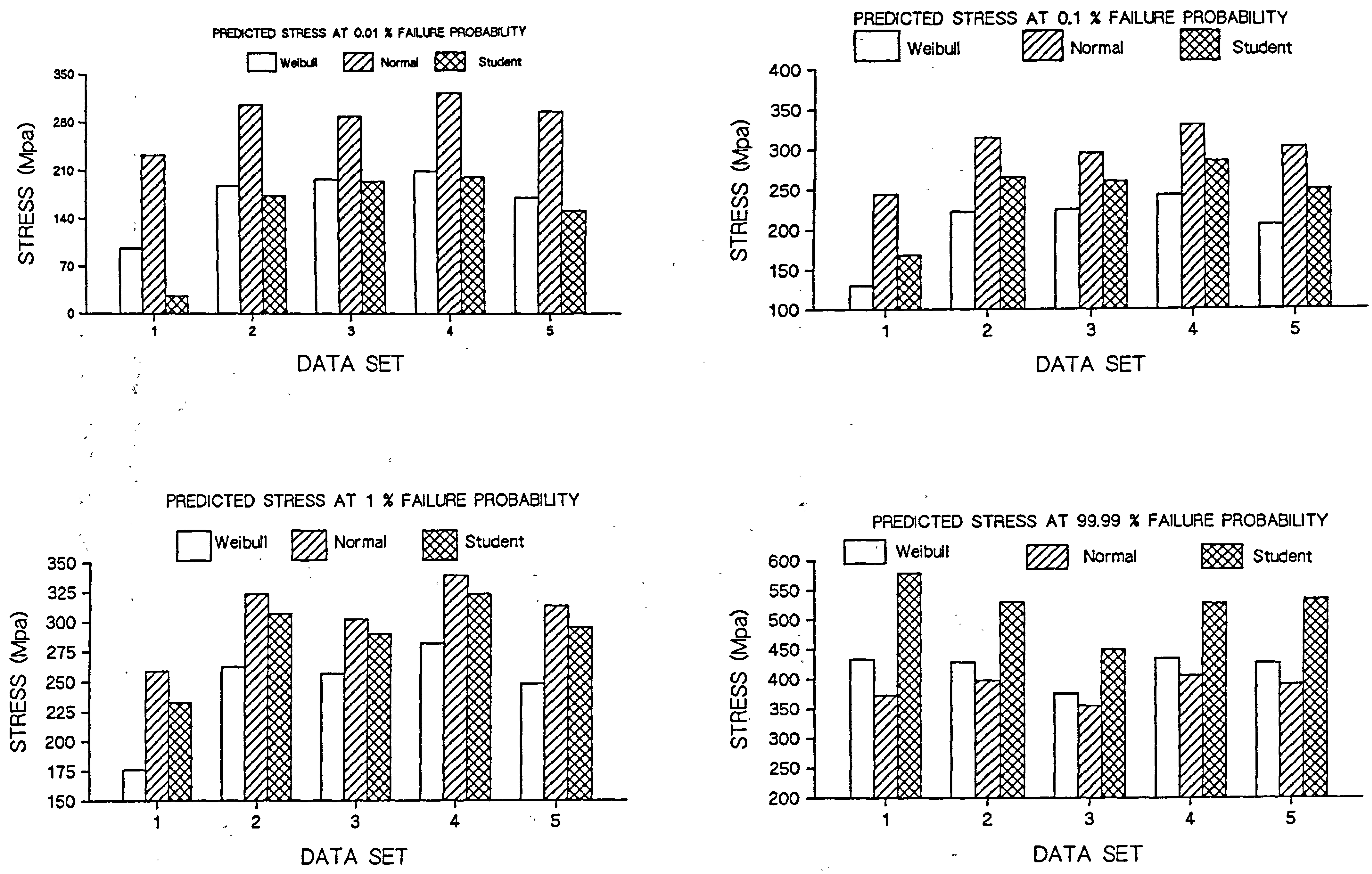


FIGURE 8.3.2.1(c) - Dry Compressive strength of Amalcap. Predicted stress at various failure probability levels.

TABLE 8.3.2.2(a)

Summary of Weibull analysis-Compressive strength of Dispersalloy for the specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1mm/min.

Conditions		Wet	Dry
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation		10.1 352.7 0.36 0.97	14.9 371.1 0.67 0.95
Mean Strength+ Deviation Coefficient (%)		336.5 10.5	359.0 7.2
Estimated Stress+ at Failure Probability			
0.01%	- Weibull Normal	141.9 312.6	200.3 341.5
1%	- Weibull Normal	223.9 321.5	272.8 348.0
99.99%	- Weibull Normal	410.2 360.4	411.1 376.5

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at 34°C, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.

Oneway analysis of variance - Highly significant difference between the strength of the specimens stored in wet condition compered with the strength of the specimens stored in dry condition ($P < 0.05$).

TABLE 8.3.2.2(b)

(i) Wet Compressive strength of Dispersalloy. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5
Data+1	322.3	354.1	310.4	366.1	346.2
Data+2	256.6	382.0	338.2	342.2	314.3
Data+3	284.5	324.3	342.2	332.2	330.2
Data+4	374.0	318.3	328.3	397.9	328.3
Data+5	274.5	380.0	290.5	384.0	397.9
Mean Strength+	302.4	351.7	321.9	364.5	343.4
Deviation Coefficient (%)	13.81	7.62	5.96	6.76	8.46
Weibull Modulus	7.6	14.0	18.0	15.8	12.5
Characteristic Strength+	322.5	364.5	331.1	376.3	357.3

(ii) Dry Compressive strength of Dispersalloy. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5	6
Data+1	378.0	374.8	395.9	413.8	356.1	364.1
Data+2	326.3	308.4	330.2	322.3	382.0	360.1
Data+3	378.0	322.3	342.2	382.0	378.0	348.2
Data+4	366.9	336.2	336.2	389.9	326.3	378.0
Data+5	368.0	372.0	358.1	389.0	330.2	378.0
Mean Strength+	363.4	342.7	352.5	379.6	354.5	365.7
Deviation Coefficient (%)	5.28	7.75	6.69	8.05	6.55	3.1
Weibull Modulus	20.4	13.7	16.0	13.2	16.3	35.1
Characteristic Strength+	372.7	366.4	363.8	394.2	365.7	371.4

+ unit in Mpa.
* Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing. Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34^{o}C , 100% humidity prior testing.

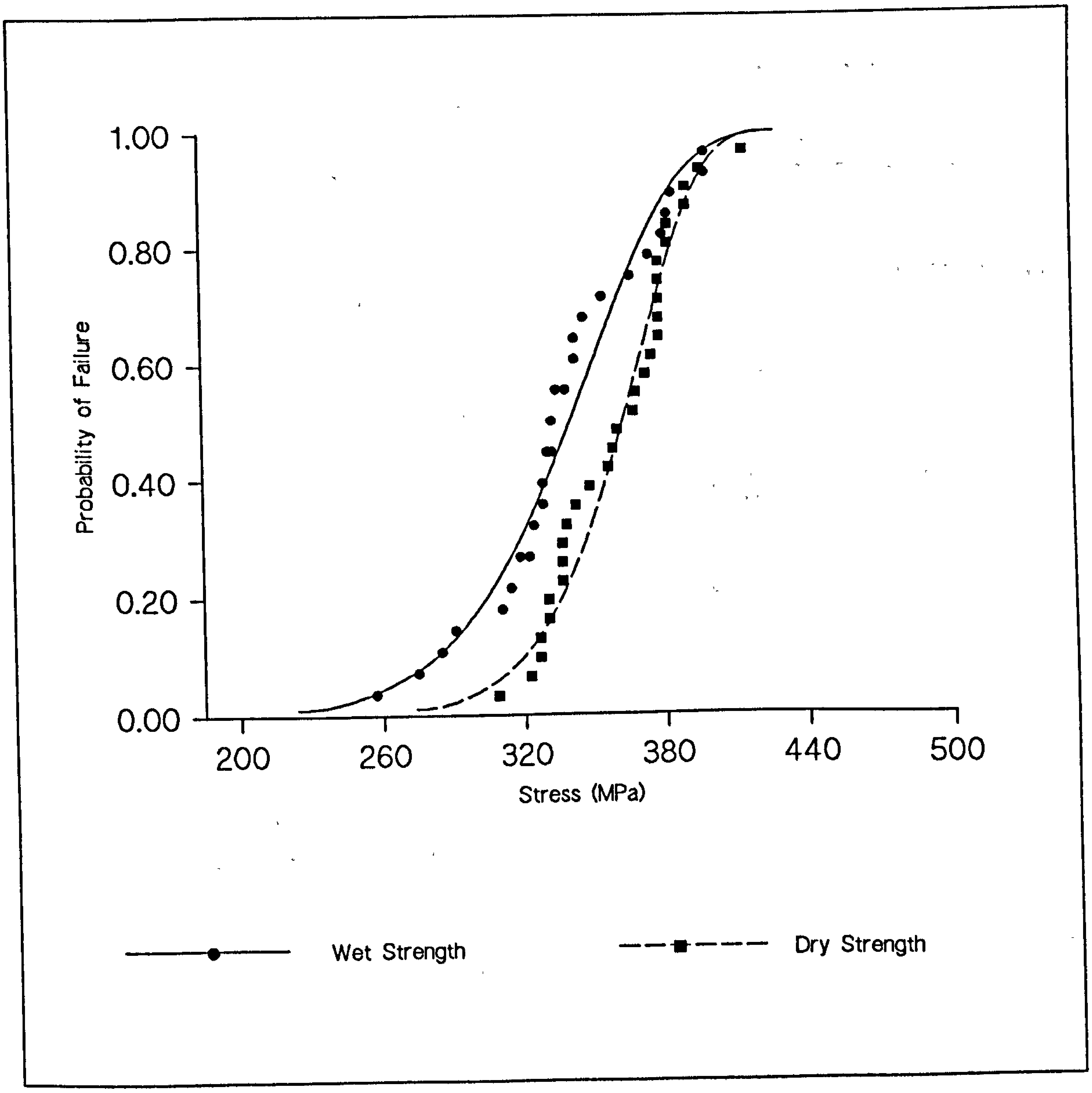


FIGURE 8.3.2.2(a)

Compressive strength of Dispersalloy-Probability of failure versus compressive stress for the specimens of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1mm/min.

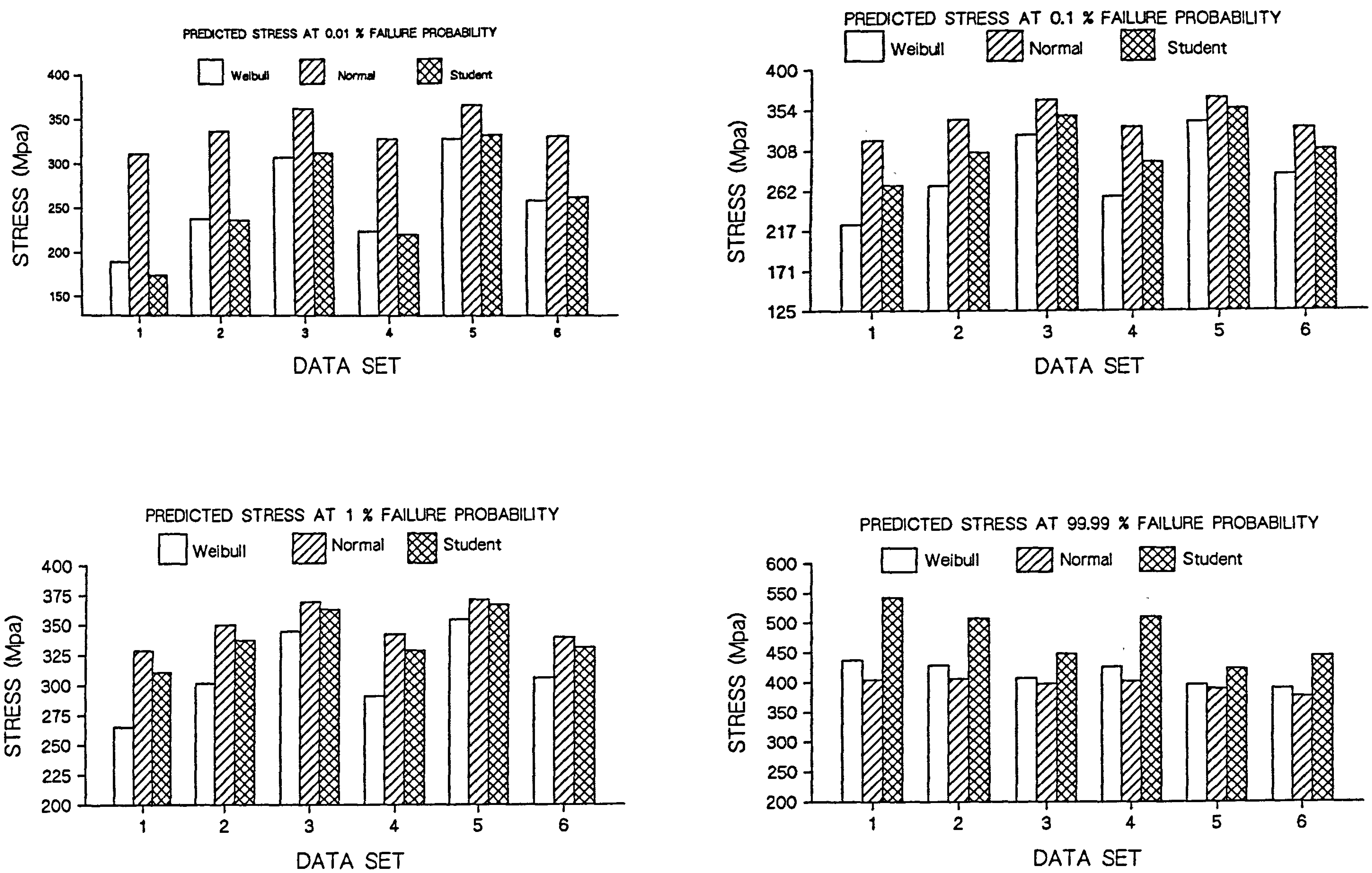


FIGURE 8.3.2.2(b) - Wet Compressive strength of Dispersalloy. Predicted stress at various failure probability levels.

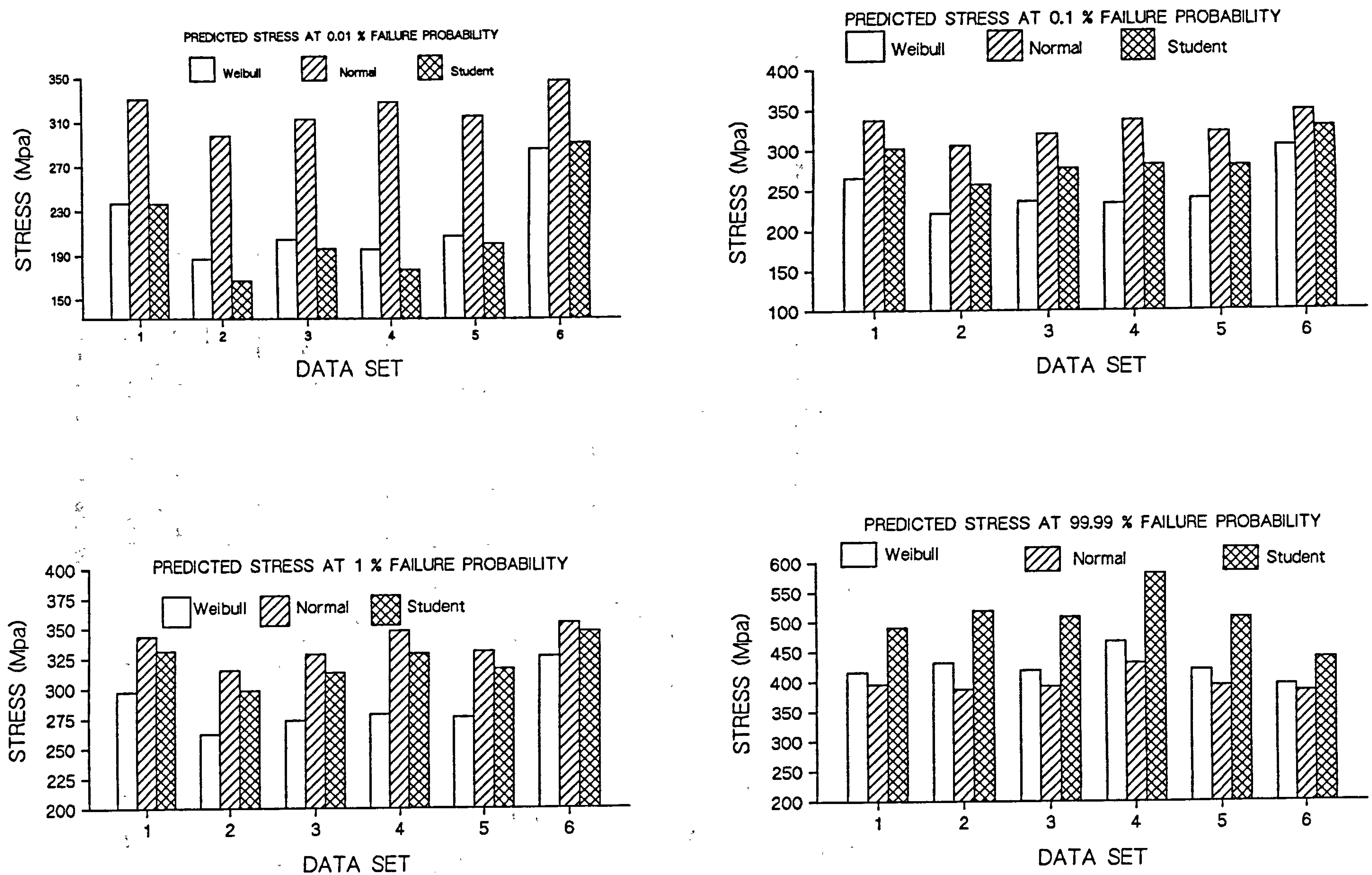


FIGURE 8.3.2.2(c) - Dry Compressive strength of Dispersalloy. Predicted stress at various failure probability levels.

TABLE 8.3.3.1(a)

Summary of Weibull analysis-Compressive strength of Dental Cements for the specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1mm/min.

Type of Dental Cements		A	B
Weibull Modulus		7.3	14.9
Characteristic Strength+		222.2	188.4
Standard Error of Modulus		0.2	0.56
Coeff. of Correlation		0.98	0.96
Mean Strength+		208.8	182.3
Deviation Coefficient (%)		14.2	7.36
Estimated Stress+ at Failure Probability			
0.01%	- Weibull	63.1	101.5
	Normal	188.8	173.2
1%	- Weibull	118.4	138.3
	Normal	196.2	176.6
99.99%	- Weibull	273.8	208.8
	Normal	228.8	191.4

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34^{o}C, 100% humidity prior testing.

A - Ketac-Fil B - Ketac-Silver

TABLE 8.3.3.1(b)

(i) Wet Compressive strength of Ketac-Fil. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5	6
Data+1 Data+2 Data+3 Data+4 Data+5	260.7 199.0 205.0 199.0 211.0	101.5 211.0 191.1 254.8 215.0	222.9 139.3 109.5 215.0 159.2	244.8 99.5 173.2 242.8 157.2	163.2 195.1 222.9 217.0 87.6	199.0 199.0 93.5 252.8 228.9
Mean Strength+ Deviation Coefficient (%)	215.0 10.8	194.7 26.2	169.2 25.8	183.5 30.0	177.1 27.9	194.7 28.0
Weibull Modulus Characteristic Strength+	9.71 226.1	3.93 220.4	4.0 191.2	3.4 211.7	3.7 202.3	3.7 222.3

(ii) Wet Compressive strength of Ketac-Silver. Each batch of 5 specimens * of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1 mm/min.

Batch no	1	2	3	4	5	6
Data+1 Data+2 Data+3 Data+4 Data+5	175.2 161.2 177.1 167.2 195.1	181.1 199.0 157.2 149.3 147.3	165.2 191.1 173.2 161.2 159.2	177.1 183.1 187.1 193.0 193.0	177.1 183.1 177.1 189.1 191.1	179.1 191.1 236.9 187.1 189.1
Mean Strength+ Deviation Coefficient (%)	175.2 6.55	166.8 12.1	170.0 6.81	186.7 3.26	183.5 3.17	196.7 10.4
Weibull Modulus Characteristic Strength+	16.3 180.7	8.7 176.4	15.7 175.5	33.4 189.7	34.4 186.4	10.1 206.5

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34^{o}C , 100% humidity prior testing.

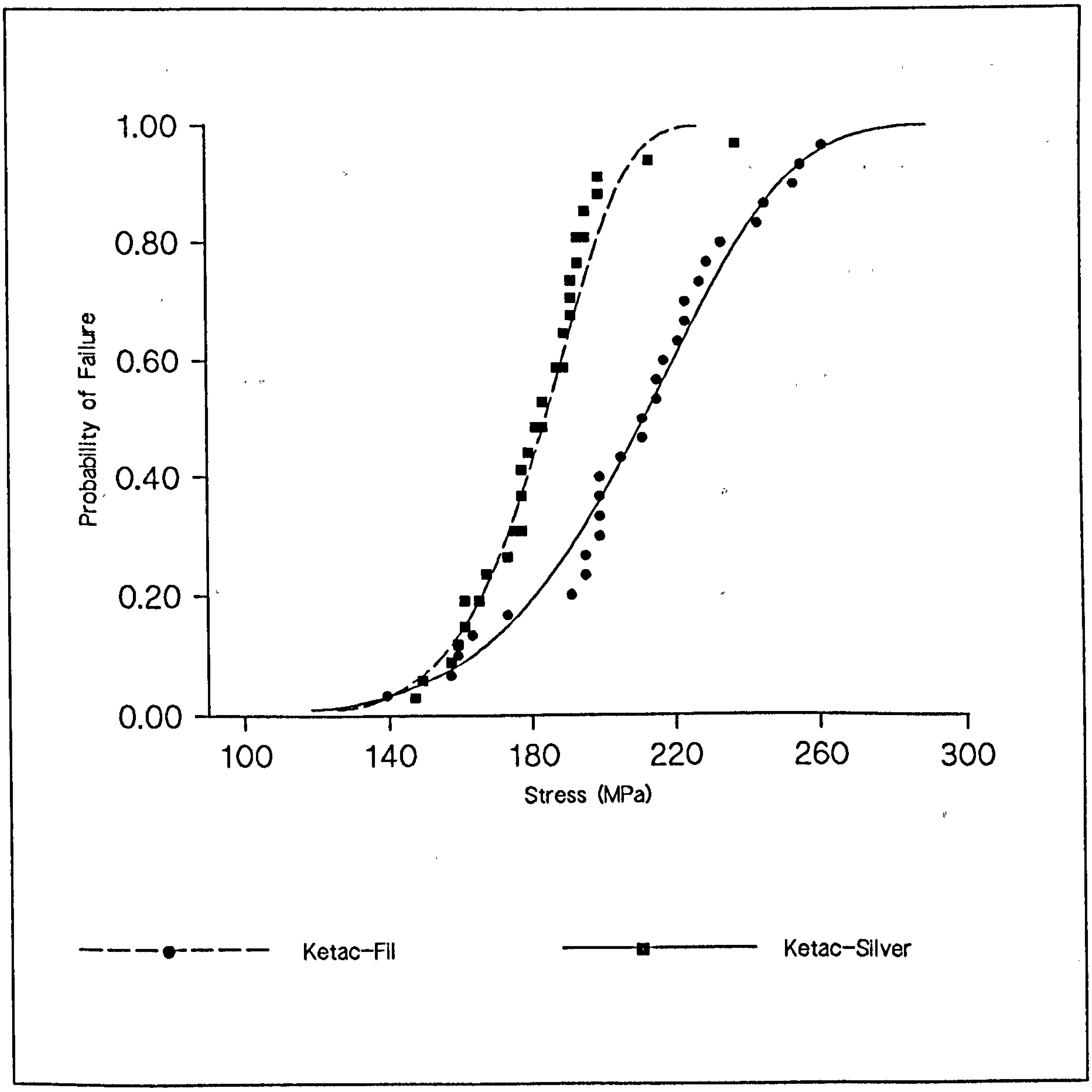


FIGURE 8.3.3.1(a)
Compressive strength of Dental Cements-Probability of failure versus compressive stress for the specimens of size 4mm diameter by 6mm length which were tested at crosshead speed 0.1mm/min.

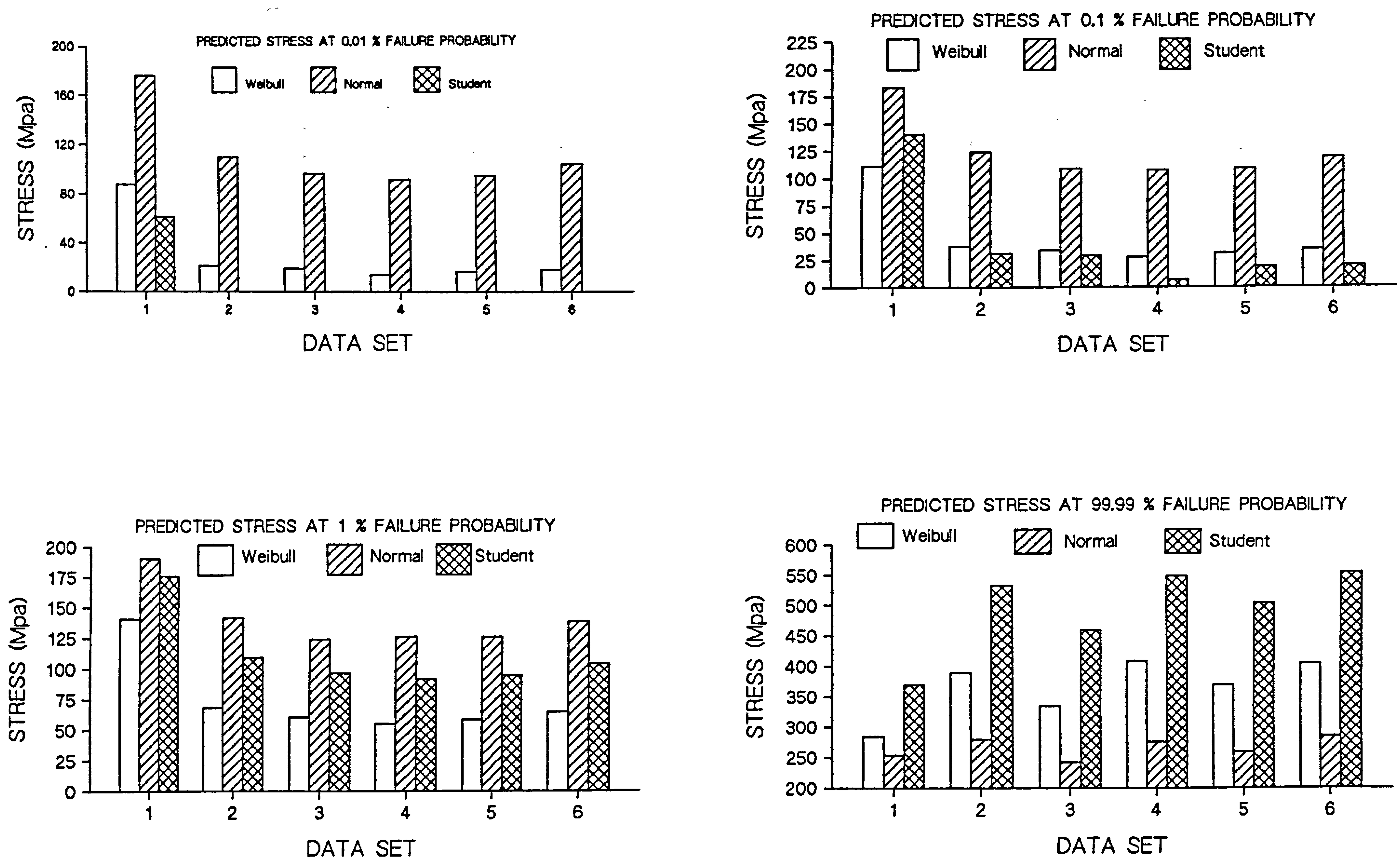


FIGURE 8.3.3.1(b) - Wet Compressive strength of Ketac-Fil. Predicted stress at various failure probability levels.

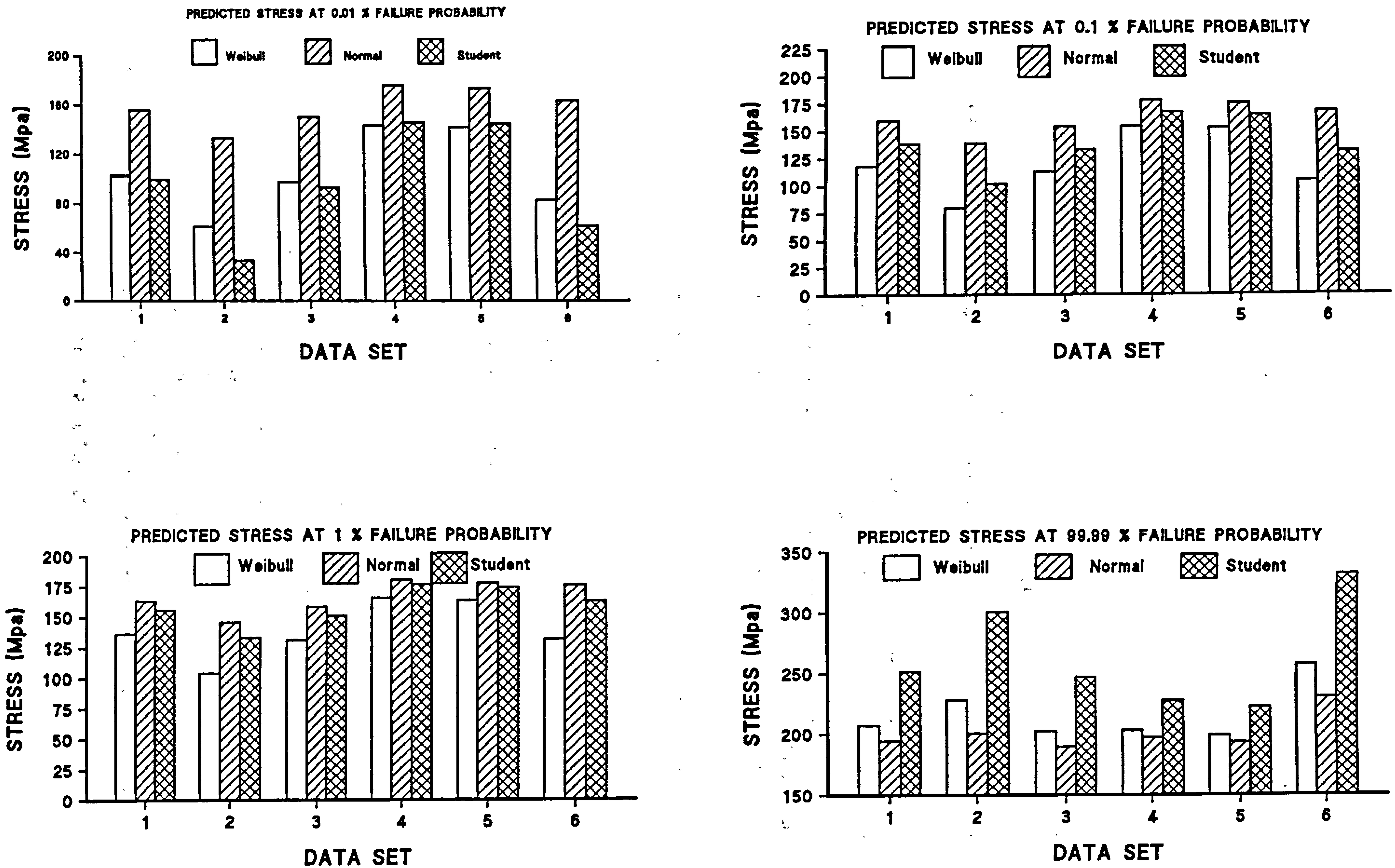


FIGURE 8.3.3.1(c) - Wet Compressive strength of Ketac-Silver. Predicted stress at various failure probability levels.

TABLE 8.3.4.1(a)

Summary of Weibull analysis-Diametral Tensile strength of Occlusin for the specimens* of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5mm/min.

Conditions		Wet	Dry
Weibull Modulus		21.1	16.7
Characteristic Strength+		55.7	54.3
Standard Error of Modulus		0.44	0.77
Coeff. of Correlation		0.99	0.94
Mean Strength+		54.4	52.7
Deviation Coefficient (%)		5.2	6.3
Estiamted Stress+ at Failure Probability			
0.01%	- Weibull	36.0	31.3
	Normal	52.5	48.8
1%	- Weibull	44.8	41.2
	Normal	53.2	50.2
99.99%	- Weibull	59.9	59.5
	Normal	56.3	56.6

+ unit in Mpa.

* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at $34^{o}C$, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.

Oneway analysis of variance-Highly significant difference between strength of the specimens stored in wet condition compared with the strength of the specimens stored in dry condition ($P < 0.05$).

TABLE 8.3.4.1(b)

(i) Wet Diametral Tensile strength of Occlusin. Each batch of 5 specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5 mm/min.

Batch no	1	2	3	4	5	6
Data+1	53.8	59.7	57.6	57.6	52.8	53.9
Data+2	54.7	55.5	48.0	54.4	56.8	52.5
Data+3	48.6	58.4	53.6	51.2	51.0	53.3
Data+4	56.5	56.5	54.1	55.5	51.0	50.7
Data+5	52.5	57.9	55.7	54.1	55.2	55.7
Mean Strength+	53.8	57.6	53.8	54.6	53.3	53.2
Deviation Coefficient (%)	5.64	2.56	5.96	3.79	4.36	3.1
Weibull Modulus	19.0	42.9	18.0	28.6	24.8	35.2
Characteristic Strength+	55.3	58.3	55.4	55.6	54.5	54.1

(ii) Dry Diametral Tensile strength of Occlusin. Each batch of 5 specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5 mm/min.

Batch no	1	2	3	4	5	6
Data+1	53.3	58.4	53.1	50.4	53.3	51.5
Data+2	52.8	49.4	51.0	57.9	51.2	56.3
Data+3	52.3	51.0	53.6	52.0	48.8	53.1
Data+4	54.7	54.1	55.2	53.6	42.5	52.0
Data+5	50.2	55.2	58.9	50.4	47.8	56.5
Mean Strength+	52.7	53.5	54.4	52.9	48.7	53.9
Deviation Coefficient (%)	2.81	6.13	4.89	5.22	7.55	3.94
Weibull Modulus	38.9	17.5	22.0	20.6	14.1	27.5
Characteristic Strength+	53.4	55.6	55.6	54.2	50.5	54.9

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34^{o}C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

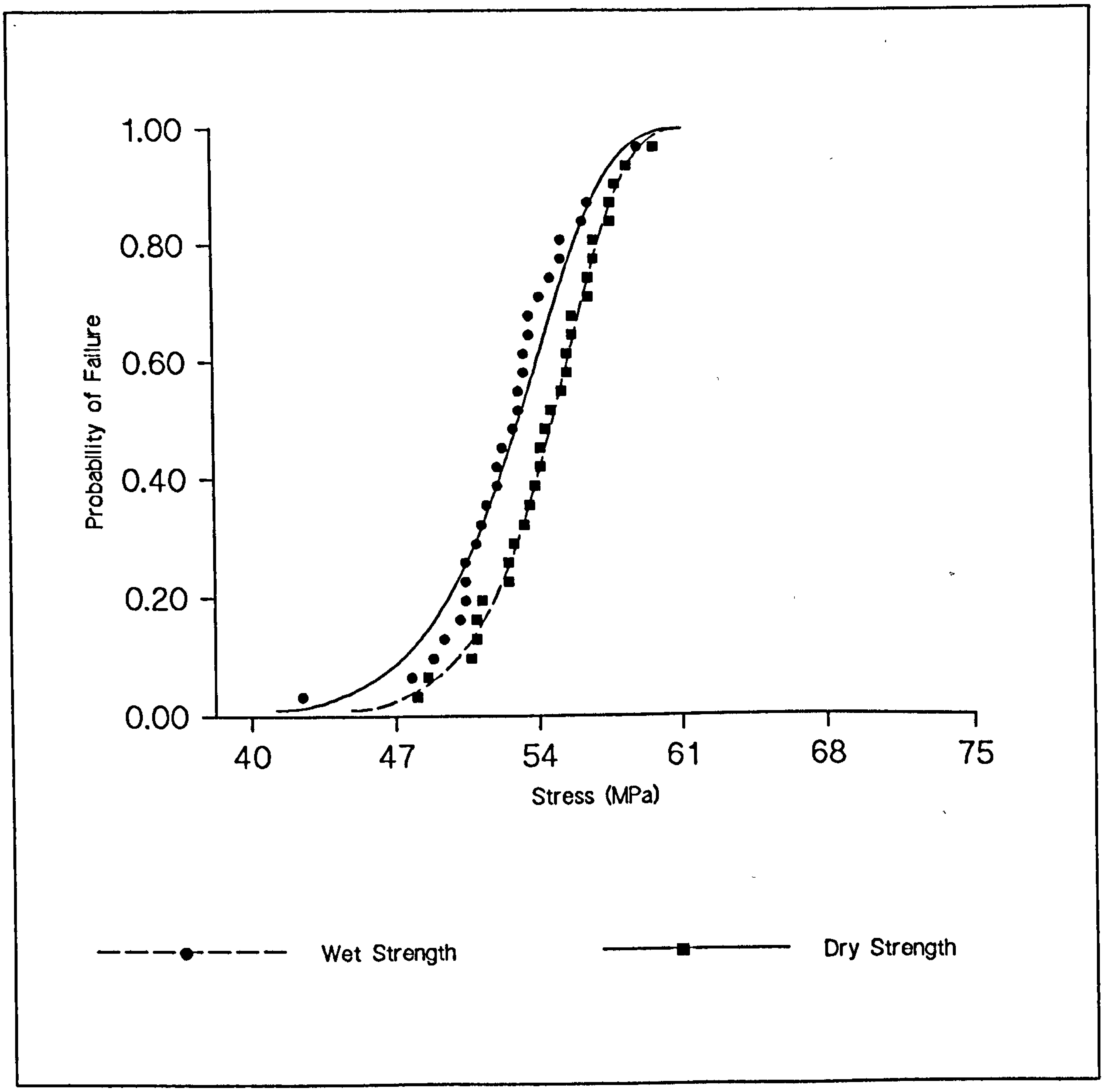


FIGURE 8.3.4.1(a)
Diametral Tensile strength of Occlusin-Probability of failure versus diametral tensile stress for the specimens of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5mm/min.

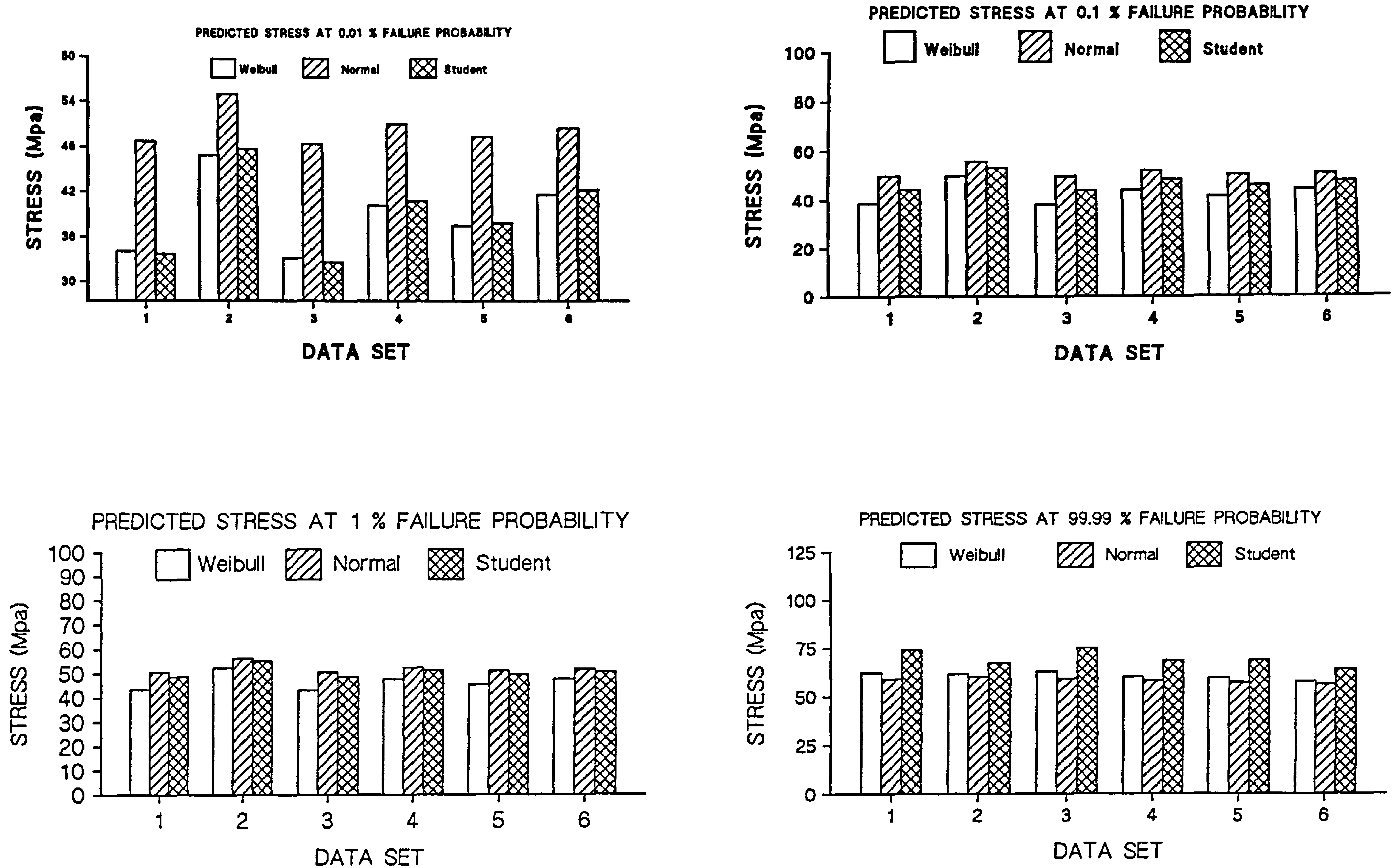


FIGURE 8.3.4.1(b) - Wet Diametral Tensile strength of Occlusin. Predicted stress at various failure probability levels.

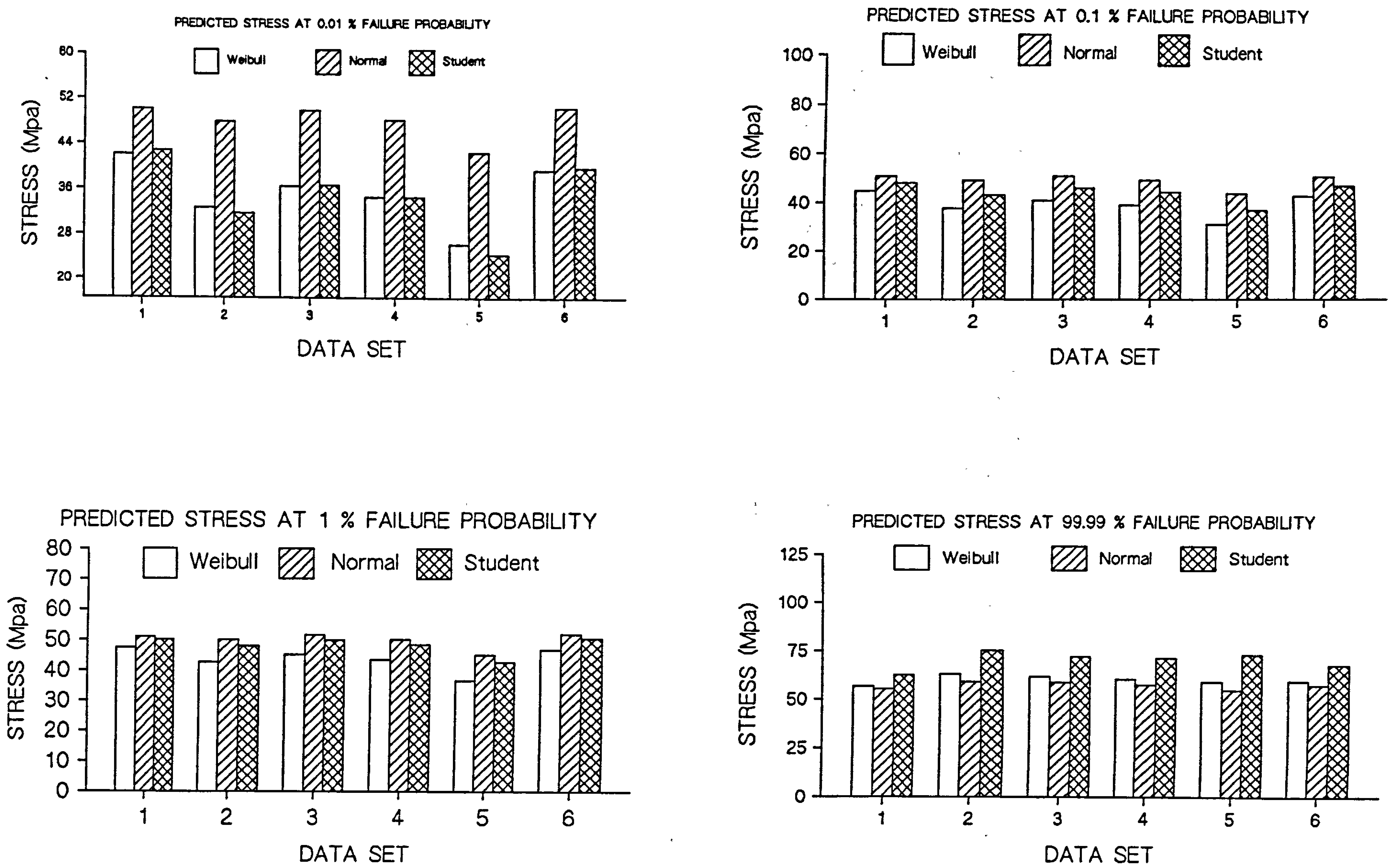


FIGURE 8.3.4.1(c) - Dry Diametral Tensile strength of Occlusin. Predicted stress at various failure probability levels.

TABLE 8.3.4.2(a)

Summary of Weibull analysis-Diametral Tensile strength of Silux for the specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5mm/min.

Conditions		Wet	Dry
Weibull Modulus		12.2	9.3
Characteristic Strength+		37.8	35.4
Standard Error of Modulus		0.23	0.49
Coeff. of Correlation		0.99	0.93
Mean Strength+		36.4	33.6
Deviation Coefficient (%)		8.9	11.5
Estimated Stress+ at Failure Probability			
0.01%	- Weibull	17.7	13.1
	Normal	34.2	31.0
1%	- Weibull	31.5	21.5
	Normal	35.0	32.0
99.99%	- Weibull	42.9	41.8
	Normal	38.6	36.2

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at 34^{o}C, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.

Oneway analysis of variance-Very highly significant difference between strength of the specimens stored in wet condition compared with the strength of the specimens stored in dry condition ($P < 0.001$).

TABLE 8.3.4.2(b)

(i) Wet Diametral Tensile strength of Silux. Each batch of 5 specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5 mm/min.

Batch no	1	2	3	4	5	6
Data+1	35.6	42.7	38.2	32.1	36.6	38.7
Data+2	39.0	36.9	30.8	35.6	34.2	37.2
Data+3	37.7	39.3	38.2	35.8	32.9	34.0
Data+4	40.6	34.2	31.8	39.3	28.7	34.0
Data+5	33.4	40.3	37.4	41.7	36.9	37.1
Mean Strength+	37.3	38.7	35.3	36.9	33.9	36.2
Deviation Coefficient (%)	6.78	7.53	9.29	8.93	8.84	5.28
Weibull Modulus	15.7	14.1	11.4	11.9	12.0	20.4
Characteristic Strength+	38.5	40.1	36.9	38.5	35.3	37.1

(ii) Dry Diametral Tensile strength of Silux. Each batch of 5 specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5 mm/min.

Batch no	1	2	3	4	5
Data+1	31.1	32.4	39.0	37.9	39.3
Data+2	31.3	33.2	31.8	26.5	30.3
Data+3	31.1	28.1	31.8	31.8	32.1
Data+4	38.7	30.8	35.3	31.8	37.7
Data+5	38.0	41.9	37.2	31.8	34.5
Mean Strength+	34.0	33.3	35.0	32.0	34.8
Deviation Coefficient (%)	10.4	14.0	8.14	11.3	9.66
Weibull Modulus	10.1	7.5	13.0	9.3	10.9
Characteristic Strength+	35.7	35.5	36.4	33.7	36.4

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34°C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

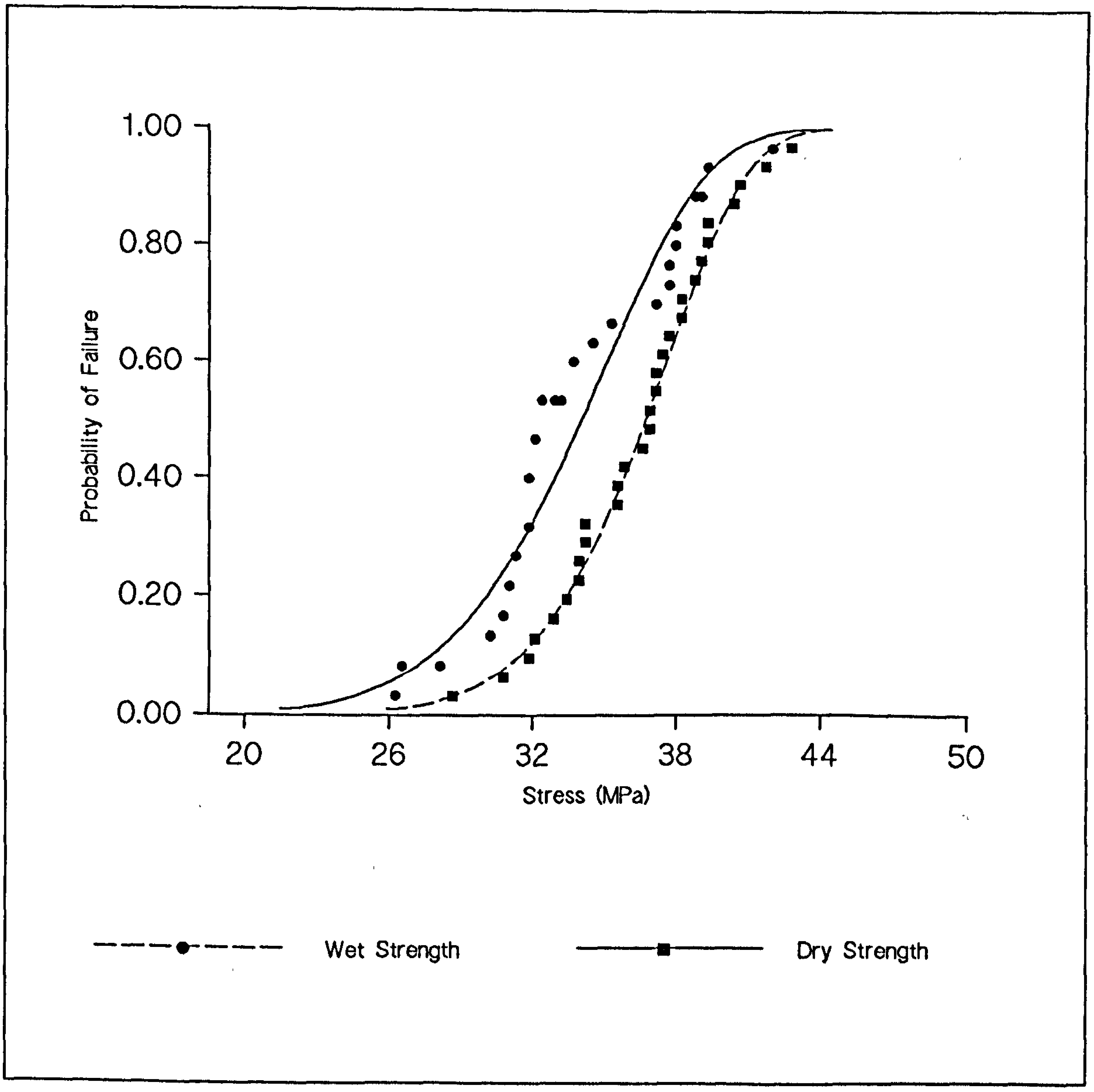


FIGURE 8.3.4.2(a)
Diametral Tensile strength of Silux-Probability of failure versus diametral tensile stress for the specimens of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5mm/min.

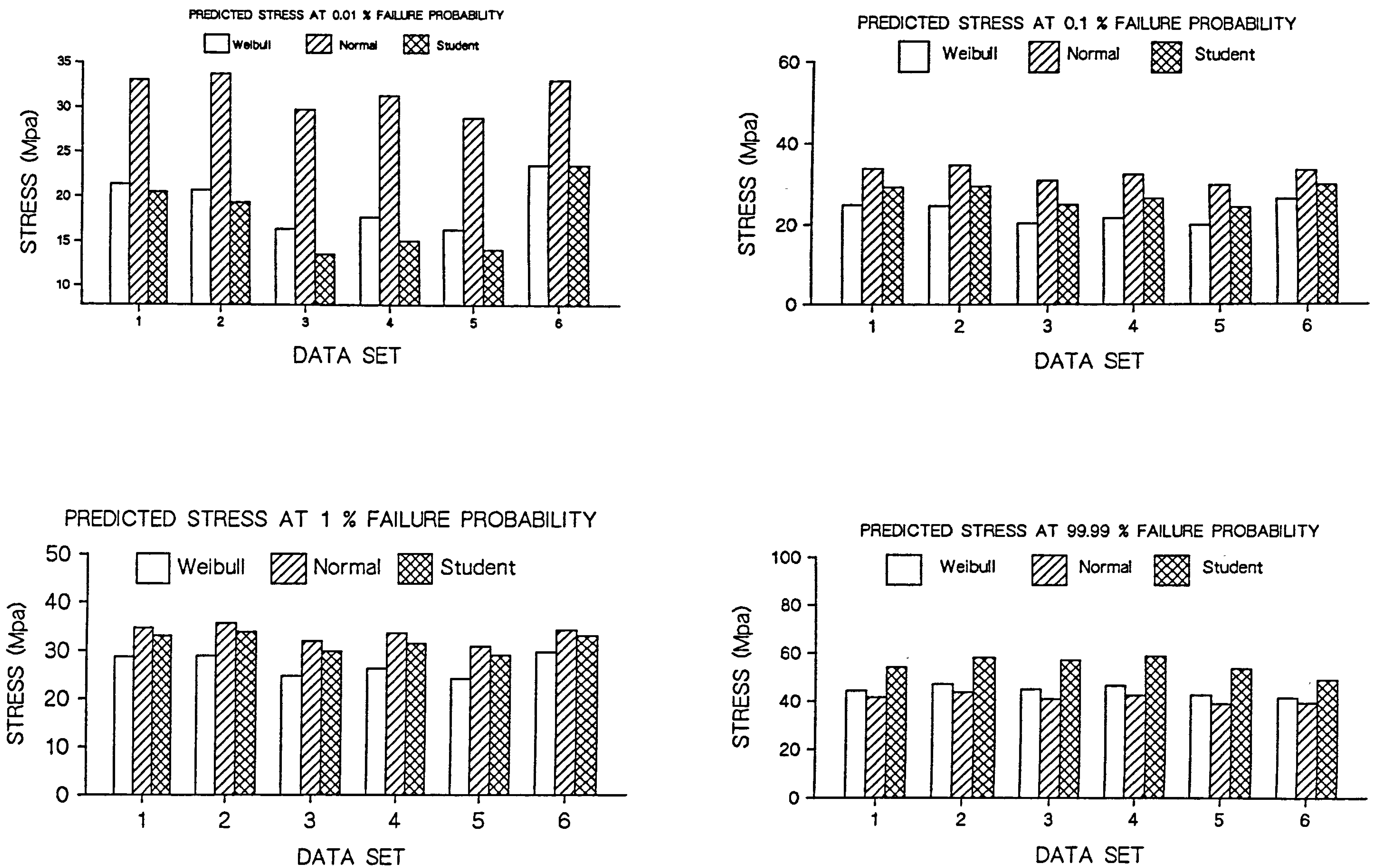


FIGURE 8.3.4.2(b) - Wet Diametral Tensile strength of Silux. Predicted stress at various failure probability levels.

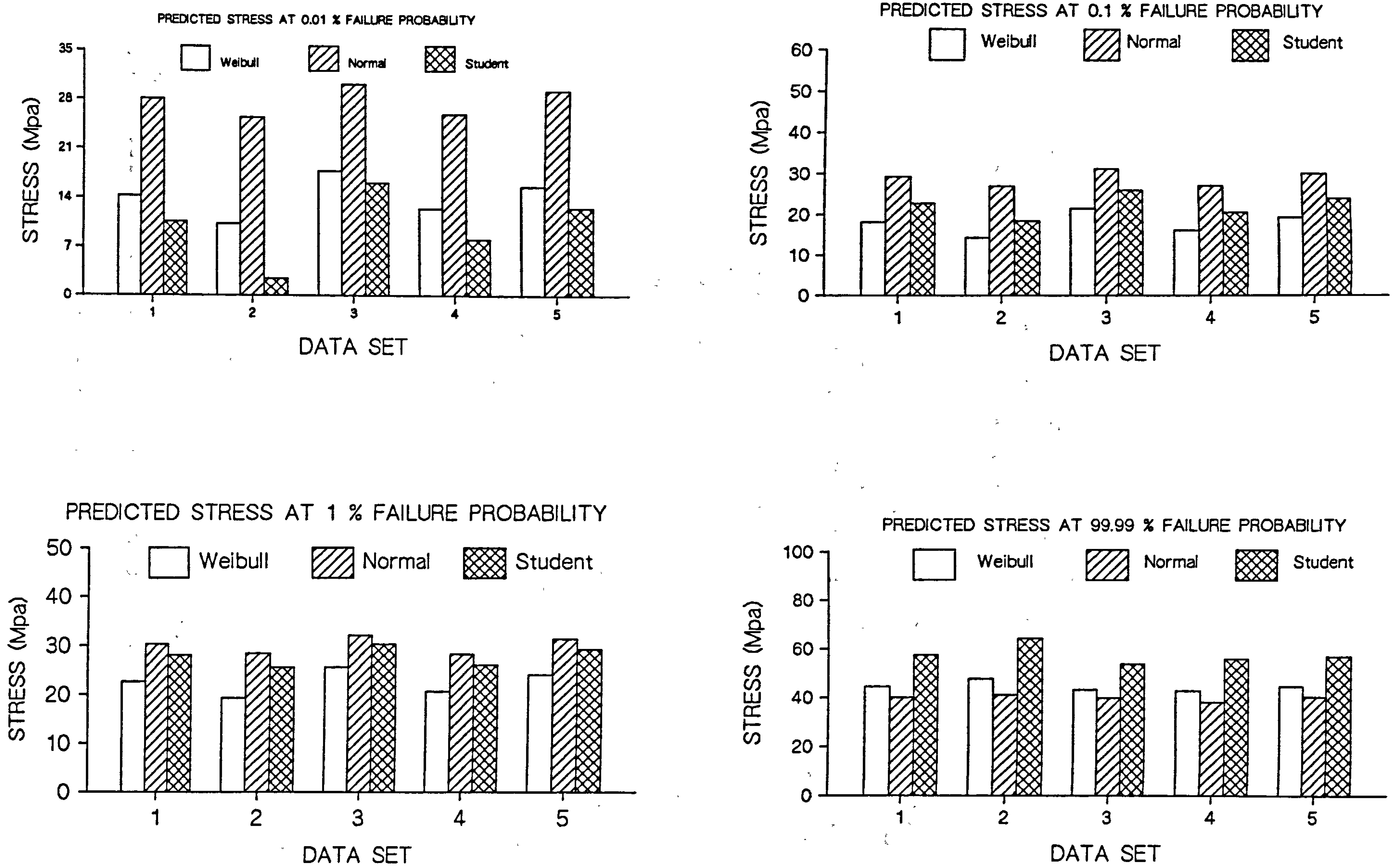


FIGURE 8.3.4.2(c) - Dry Diametral Tensile strength of Silux. Predicted stress at various failure probability levels.

TABLE 8.3.4.3(a)

Summary of Weibull analysis-Diametral Tensile strength of P50 Plus for the specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5mm/min.

Conditions		Wet	Dry
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation		9.1 61.3 0.15 0.99	7.4 54.7 0.20 0.98
Mean Strength+ Deviation Coefficient (%)		58.2 11.7	51.5 14.4
Estimated Stress+ at Failure Probability			
0.01%	- Weibull Normal	22.3 53.6	15.8 46.5
1%	- Weibull Normal	37.0 55.3	29.5 48.3
99.99%	- Weibull Normal	72.5 62.8	67.2 56.5

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at 34°C, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.

Oneway analysis of variance-Very highly significant difference between strength of the specimens stored in wet condition compared with the strength of the specimens stored in dry condition ($P < 0.001$).

TABLE 8.3.4.3(b)

(i) Wet Diametral Tensile strength of P50. Each batch of 5 specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5 mm/min.

Batch no	1	2	3	4	5	6
Data+1	52.5	42.5	63.2	66.3	58.9	55.7
Data+2	60.5	61.6	58.4	45.6	63.7	65.8
Data+3	67.9	66.9	69.5	60.5	55.2	51.0
Data+4	56.3	47.8	60.0	50.9	54.7	48.3
Data+5	58.4	61.0	55.7	61.0	58.4	67.4
Mean Strength+	59.1	55.9	61.4	56.9	58.2	57.6
Deviation Coefficient (%)	8.68	16.5	7.73	13.2	5.55	13.4
Weibull Modulus	12.2	6.3	13.8	7.95	19.3	7.8
Characteristic Strength+	61.6	60.4	63.6	60.5	59.7	61.4

(ii) Dry Diametral Tensile strength of P50. Each batch of 5 specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5 mm/min.

Batch no	1	2	3	4	5	6
Data+1	48.3	36.1	56.8	54.4	45.1	46.2
Data+2	54.7	65.6	63.2	47.8	62.6	54.4
Data+3	49.4	56.3	42.5	51.0	56.0	48.3
Data+4	37.7	59.2	48.3	52.8	53.3	49.6
Data+5	49.9	65.3	39.3	44.1	53.1	52.8
Mean Strength+	48.0	56.5	50.0	50.0	54.0	50.3
Deviation Coefficient (%)	11.7	19.1	17.7	7.41	10.4	5.94
Weibull Modulus	9.0	5.42	5.8	14.4	10.1	18.0
Characteristic Strength+	50.7	61.8	54.3	51.8	56.7	51.7

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34^{o}C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

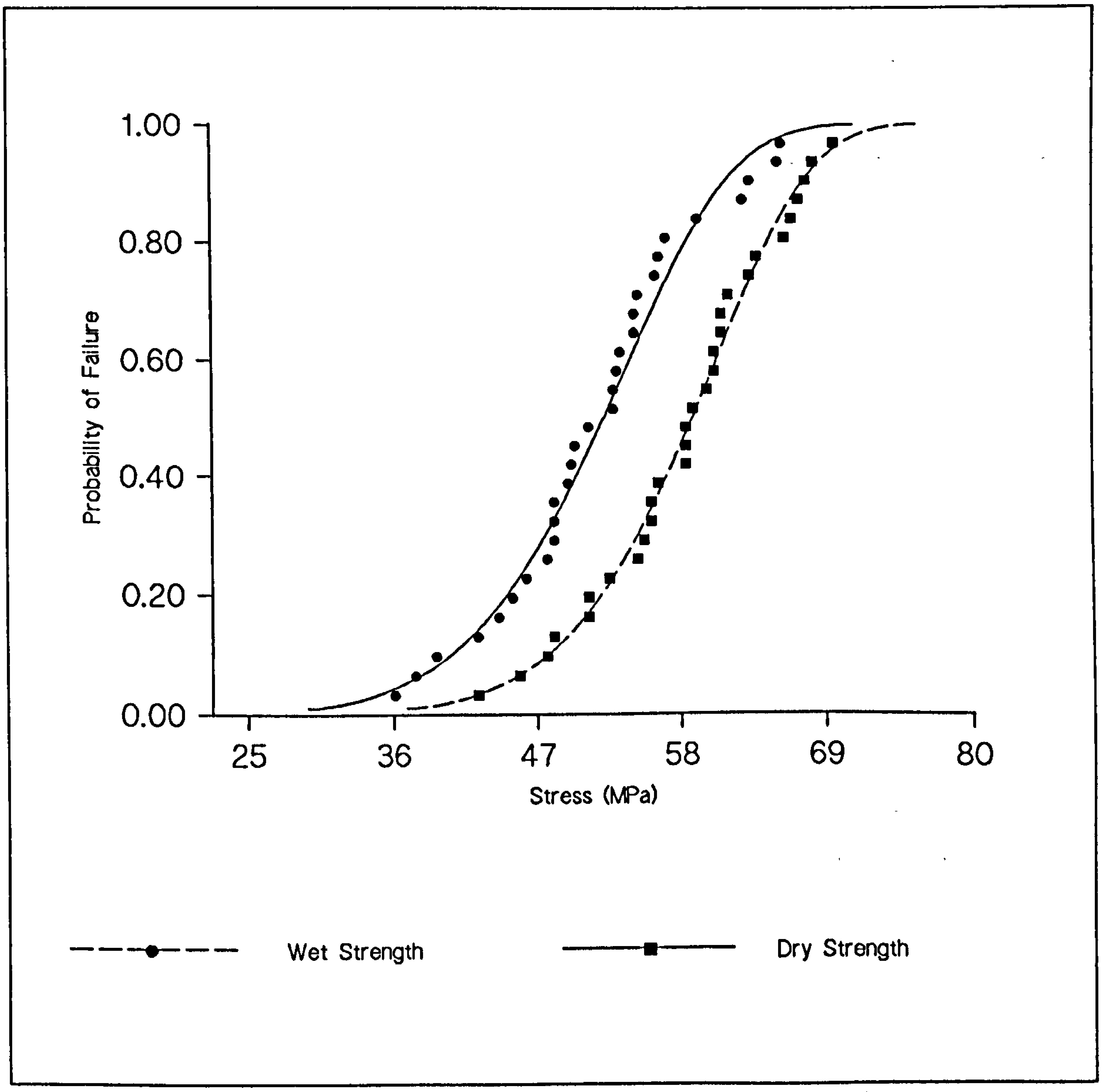


FIGURE 8.3.4.3(a)
Diametral Tensile strength of P50 Plus-Probability of failure versus diametral tensile stress for the specimens of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5mm/min.

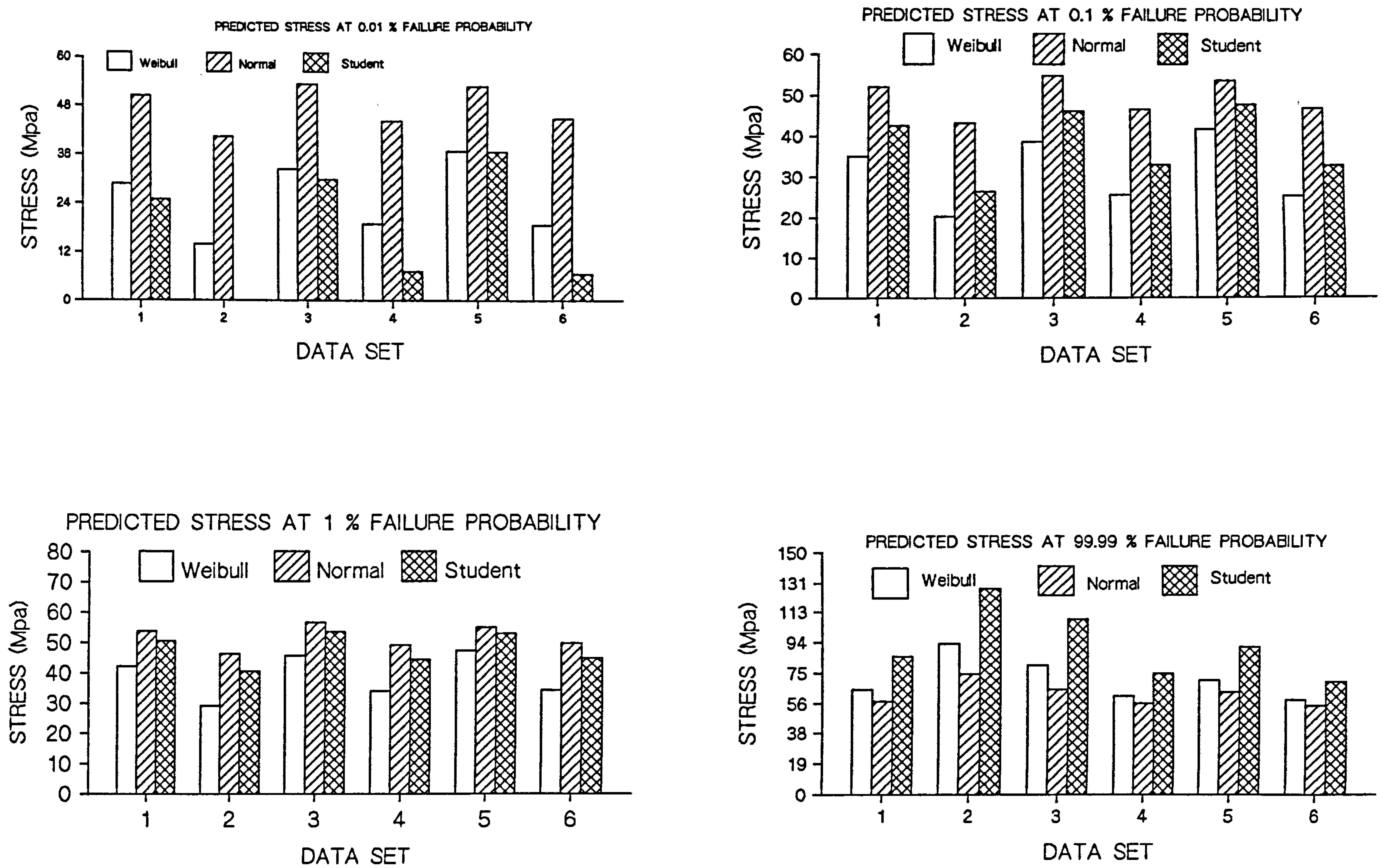


FIGURE 8.3.4.3(b) - Wet Diametral Tensile strength of P50. Predicted stress at various failure probability levels.

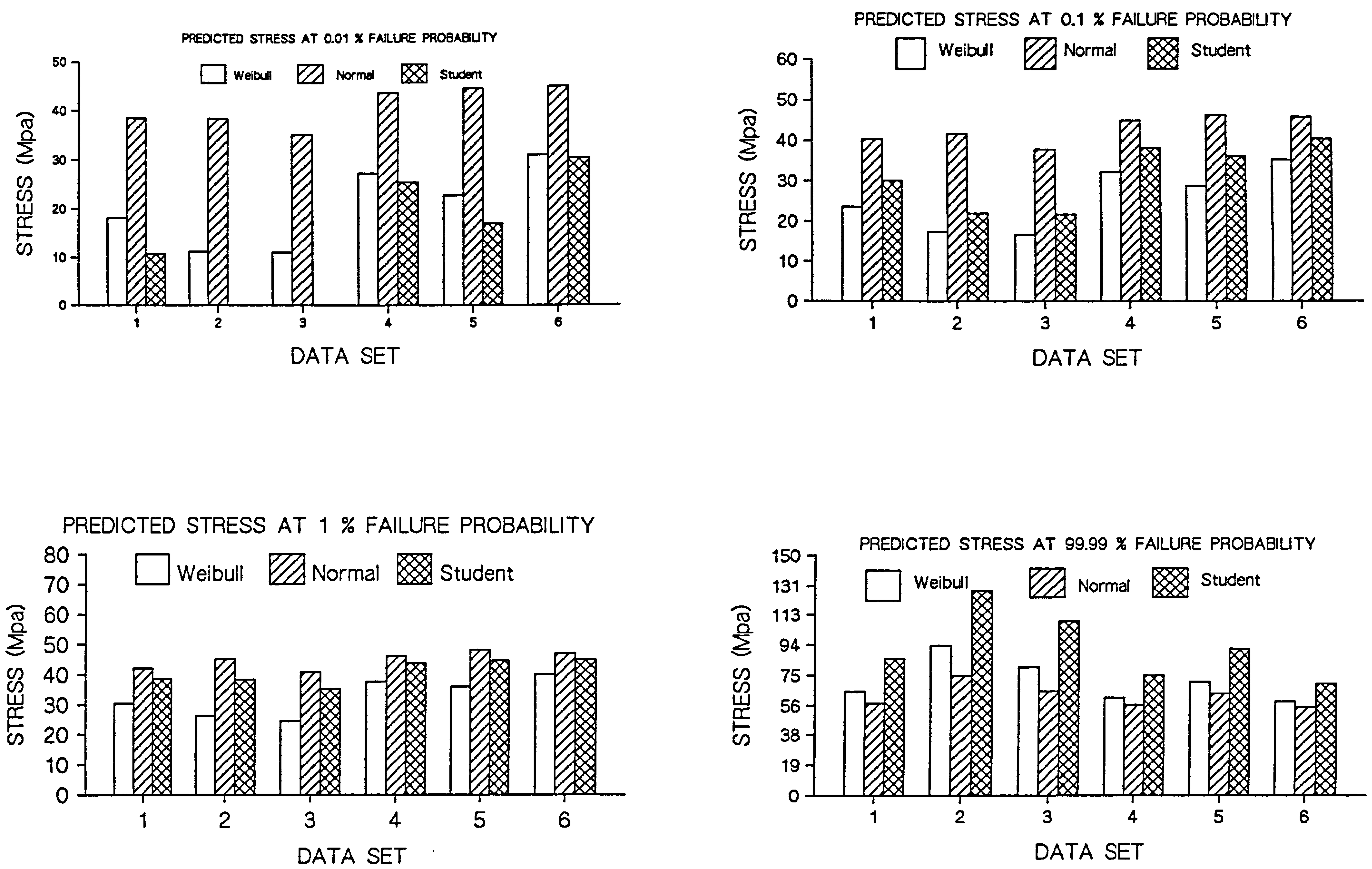


FIGURE 8.3.4.3(c) - Dry Diametral Tensile strength of P50. Predicted stress at various failure probability levels.

TABLE 8.3.5.1(a)

Summary of Weibull analysis-Diametral Tensile strength of Amalcap for the specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5mm/min.

Conditions		Wet	Dry
Weibull Modulus		6.1	7.3
Characteristic Strength+		39.5	36.8
Standard Error of Modulus		0.22	0.62
Coeff. of Correlation		0.96	0.83
Mean Strength+		36.7	34.5
Deviation Coefficient (%)		17.7	14.8
Estimated Stress+ at Failure Probability			
0.01%	- Weibull	8.7	10.4
	Normal	32.3	31.0
1%	- Weibull	18.6	19.6
	Normal	33.9	32.3
99.99%	- Weibull	50.7	45.4
	Normal	41.1	37.9

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at 34°C, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.

Oneway analysis of variance - No significant difference between the strength of the specimens stored in wet condition compared with the strength of the specimens stored in dry condition ($P>0.05$).

TABLE 8.3.5.1(b)

(i) Wet Diametral Tensile strength of Amalcap. Each batch of 5 specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5 mm/min.

Batch no	1	2	3	4	5	6
Data+1	36.1	35.8	40.9	41.9	32.9	30.8
Data+2	35.3	39.0	47.2	42.5	33.2	41.1
Data+3	46.2	44.6	50.4	26.0	28.1	35.6
Data+4	36.6	35.3	32.9	26.0	40.1	29.2
Data+5	30.5	37.2	37.7	26.5	34.8	47.2
Mean Strength+	36.9	38.4	41.8	32.6	33.8	36.8
Deviation Coefficient (%)	13.8	8.8	15.2	24.1	11.4	18.2
Weibull Modulus	7.6	12.1	6.9	4.8	9.3	5.7
Characteristic Strength+	39.4	40.0	44.9	36.5	35.7	40.1

(ii) Dry Diametral Tensile strength of Amalcap. Each batch of 5 specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5 mm/min.

Batch no	1	2	3	4	5	6
Data+1	36.6	28.4	37.4	34.5	33.4	37.9
Data+2	34.5	34.8	36.3	34.2	30.2	34.5
Data+3	42.4	44.3	31.8	34.5	29.4	27.9
Data+4	34.8	37.1	37.9	52.0	29.2	28.1
Data+5	34.2	32.9	35.5	34.2	28.4	28.9
Mean Strength+	36.5	35.5	35.8	37.9	30.1	31.5
Deviation Coefficient (%)	8.46	14.8	6.02	18.6	5.8	12.9
Weibull Modulus	12.6	7.06	17.8	5.57	18.5	8.2
Characteristic Strength+	38.0	38.0	36.9	41.3	31.0	33.4

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34°C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

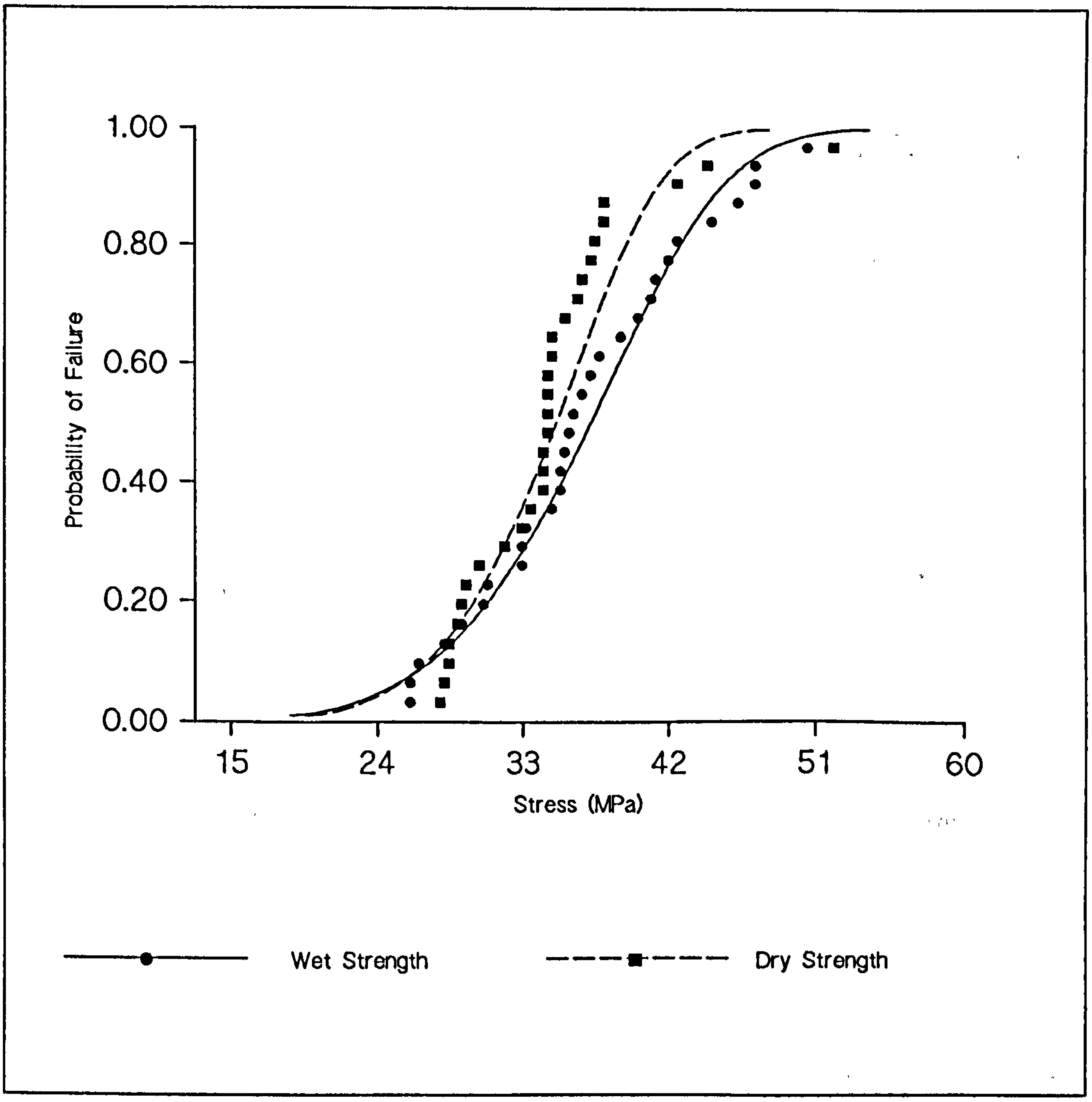


FIGURE 8.3.5.1(a)
Diametral Tensile strength of Amalcap-Probability of failure versus diametral tensile stress for the specimens of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5mm/min.

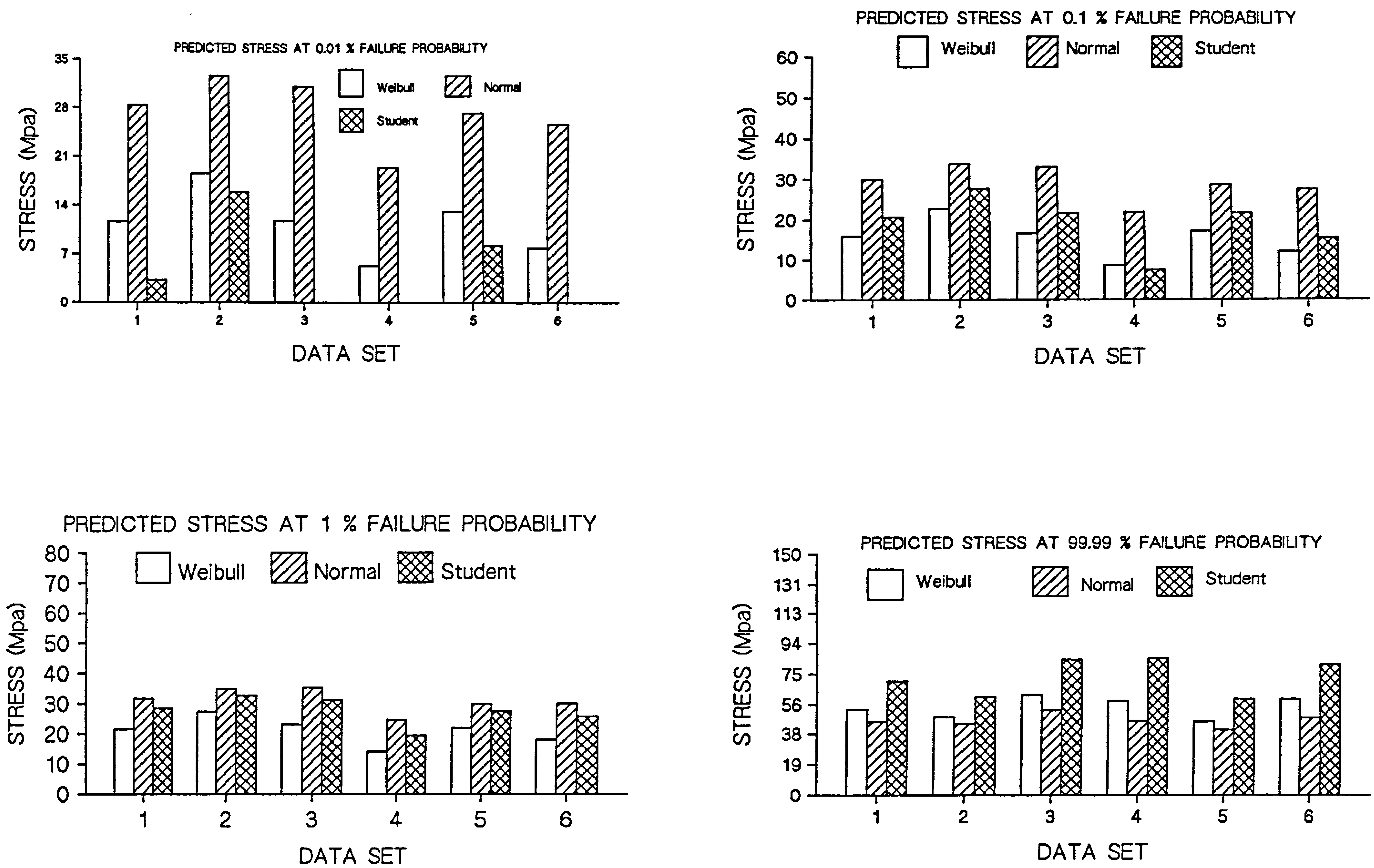


FIGURE 8.3.5.1(b) - Wet Diametral Tensile strength of Amalcap. Predicted stress at various failure probability levels.

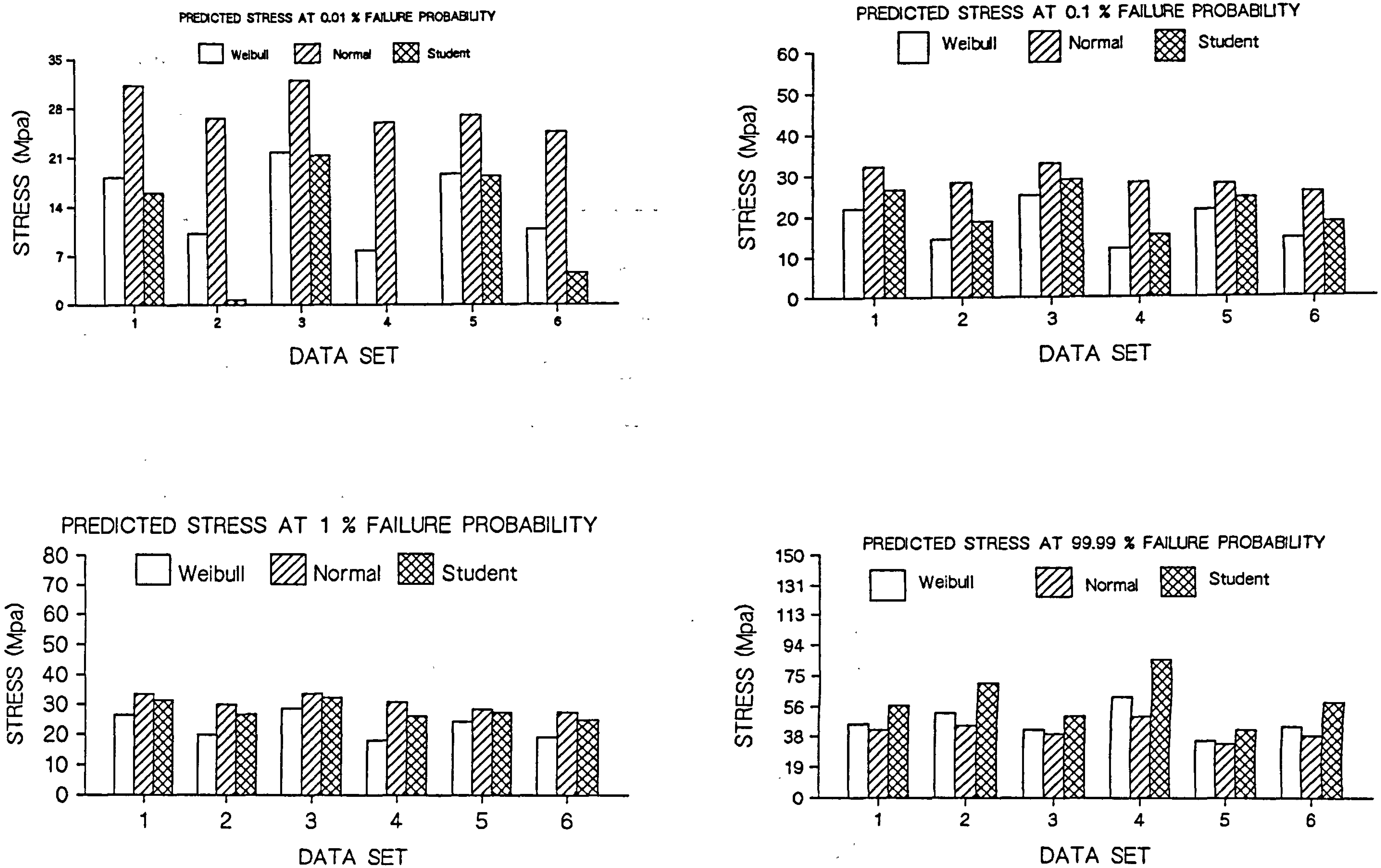


FIGURE 8.3.5.1(c) - Dry Diametral Tensile strength of Amalcap. Predicted stress at various failure probability levels.

TABLE 8.3.5.2(a)

Summary of Weibull analysis-Diametral Tensile strength of Dispersalloy for the specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5mm/min.

Conditions		Wet	Dry
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation		4.5 39.4 0.20 0.95	6.3 39.9 0.38 0.91
Mean Strength+ Deviation Coefficient (%)		36.0 24.0	37.2 16.9
Estimated Stress+ at Failure Probability			
At 0.01%	- Weibull Normal	5.2 30.2	9.2 33.0
1%	- Weibull Normal	14.3 32.3	19.2 34.5
99.99%	- Weibull Normal	55.1 41.8	50.8 41.5

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at 34°C, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.

Oneway analysis of variance - Very highly no significant difference between the strength of the specimens stored in wet condition compared with the strength of the specimens stored in dry condition ($P>0.5$).

TABLE 8.3.5.2(b)

(i) Wet Diametral Tensile strength of Dispersalloy. Each batch of 5 specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5 mm/min.

Batch no	1	2	3	4	5	6
Data+1	42.2	52.5	36.1	35.0	27.9	27.6
Data+2	21.2	33.4	39.5	45.6	35.5	43.8
Data+3	28.1	35.5	29.2	28.6	36.6	38.7
Data+4	23.9	25.5	58.4	29.7	45.1	47.2
Data+5	40.3	44.0	39.8	28.1	33.4	28.6
Mean Strength+	31.1	38.2	40.6	33.4	35.7	37.2
Deviation Coefficient (%)	27.5	24.3	23.8	19.7	15.6	21.2
Weibull Modulus	3.7	4.2	4.3	5.3	6.7	4.9
Characteristic Strength+	35.5	42.8	45.4	36.6	38.4	41.1

(ii) Dry Diametral Tensile strength of Dispersalloy. Each batch of 5 specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5 mm/min.

Batch no	1	2	3	4	5	6
Data+1	38.2	40.6	32.6	28.1	34.7	38.2
Data+2	30.8	41.6	40.8	31.6	46.4	31.8
Data+3	40.1	30.0	45.6	41.6	30.5	35.3
Data+4	44.8	29.7	46.7	29.2	35.5	49.3
Data+5	29.2	38.7	35.8	30.8	39.0	47.7
Mean Strength+	36.6	36.1	40.3	32.3	37.2	40.5
Deviation Coefficient (%)	16.0	14.4	13.5	15.0	14.3	17.1
Weibull Modulus	6.5	7.2	7.8	7.0	7.3	6.1
Characteristic Strength+	39.4	38.6	42.9	34.6	39.8	43.8

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34^{o}C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

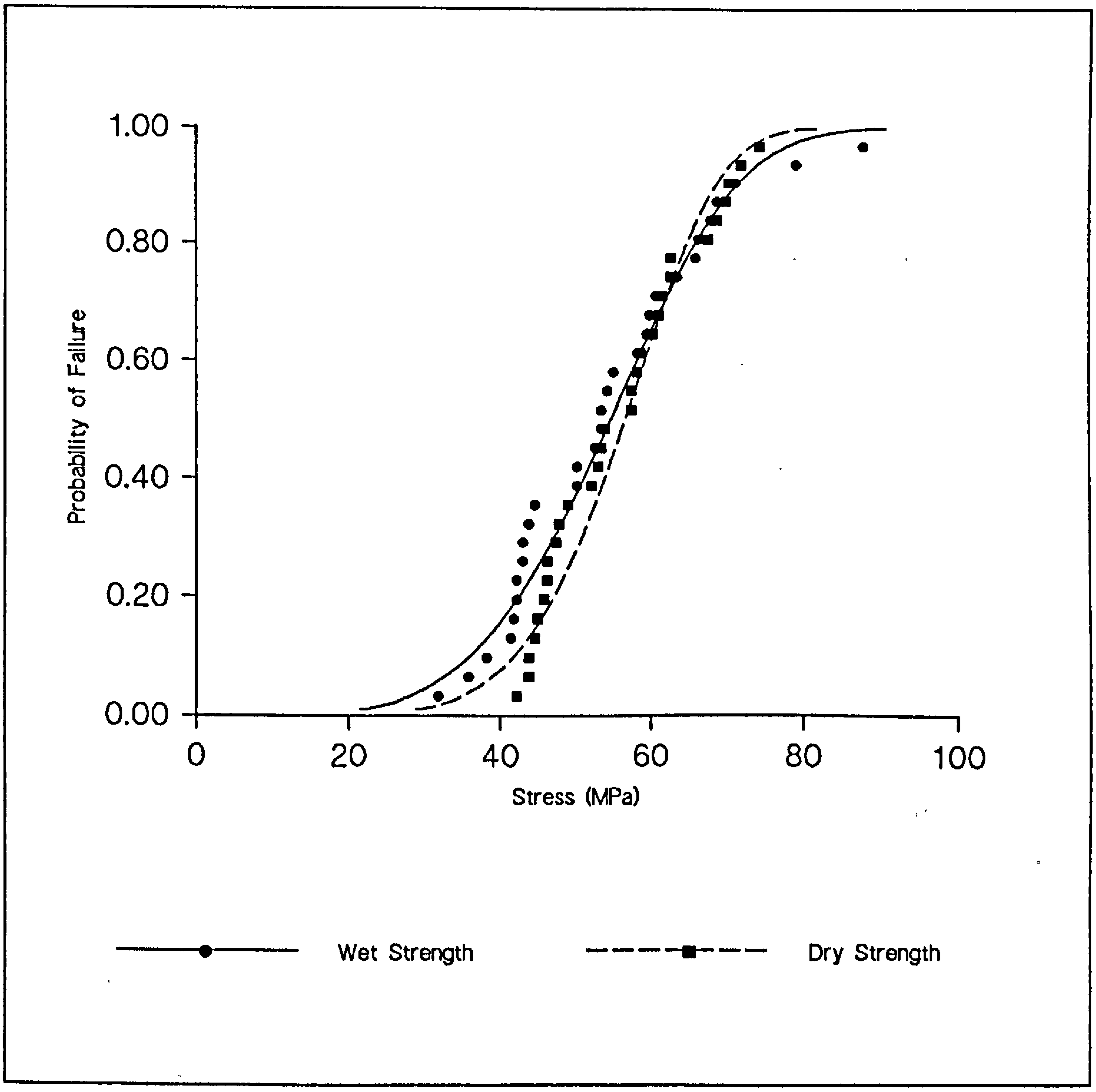


FIGURE 8.3.5.2(a)
Diametral Tensile strength of Dispersalloy-Probability of failure versus diametral tensile stress for the specimens of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5mm/min.

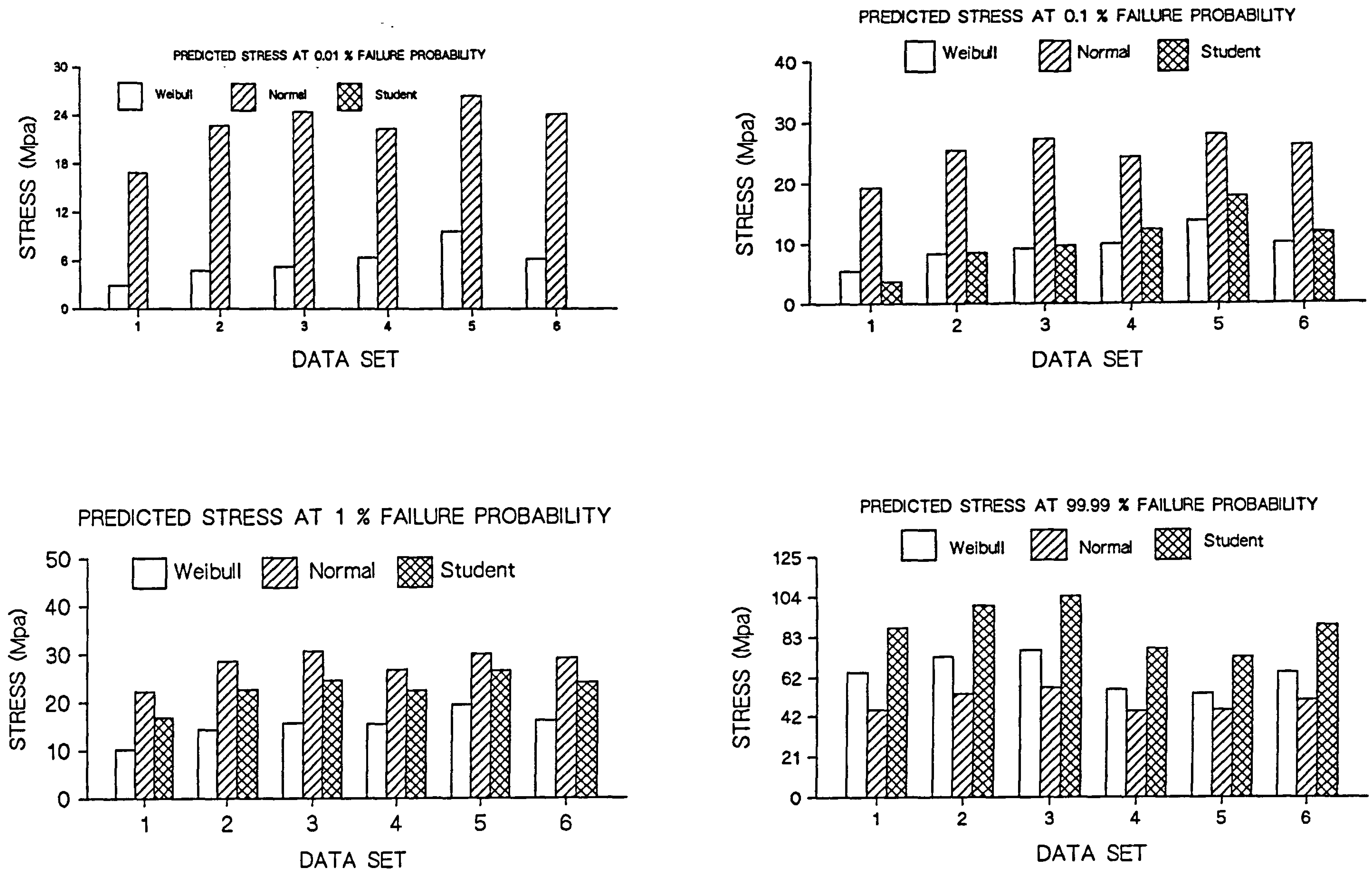


FIGURE 8.3.5.2(b) - Wet Diametral Tensile strength of Dispersalloy. Predicted stress at various failure probability levels.

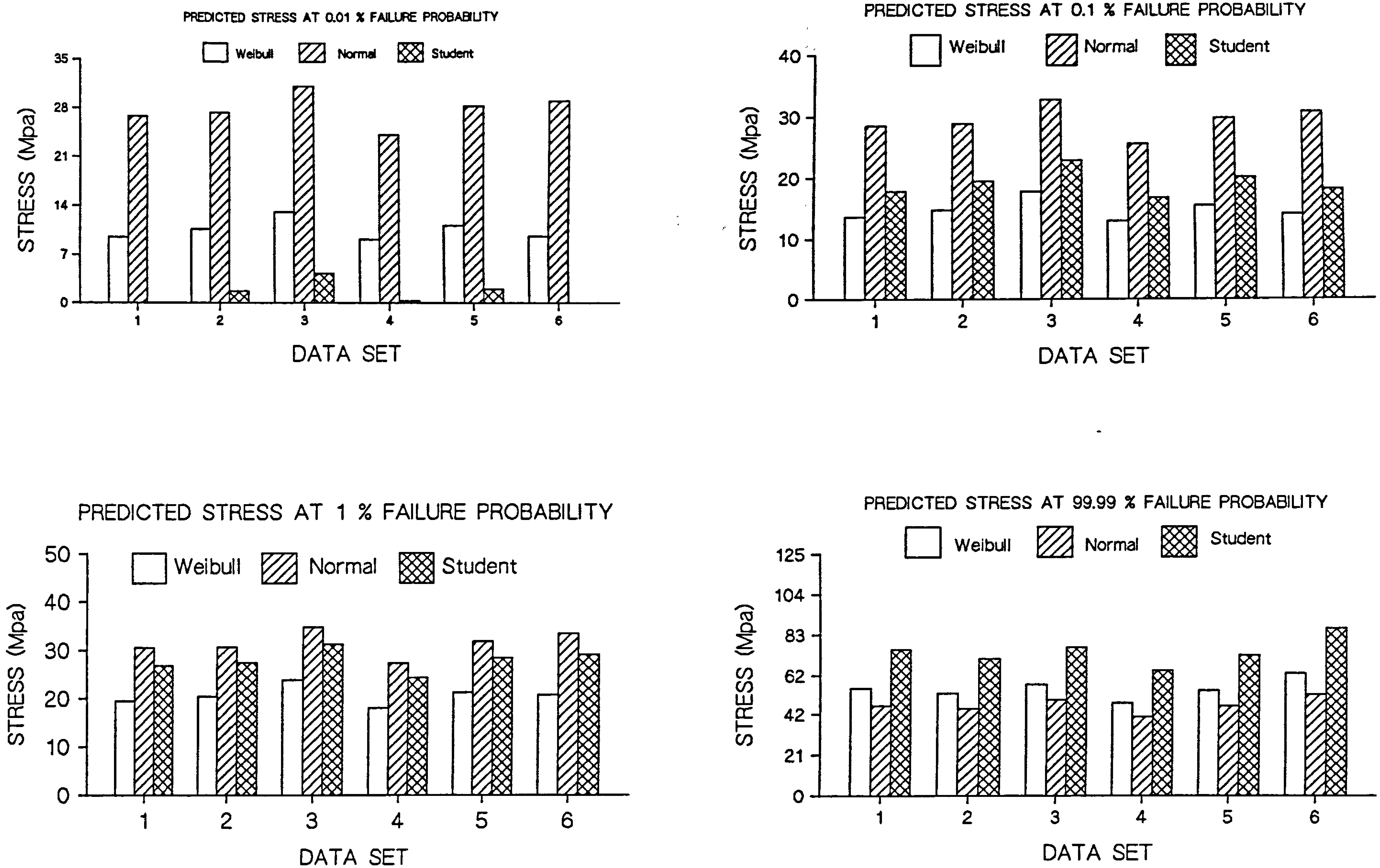


FIGURE 8.3.5.2(c) - Dry Diametral Tensile strength of Dispersalloy. Predicted stress at various failure probability levels.

TABLE 8.3.6.1(a)

Summary of Weibull analysis-Diametral Tensile strength of Dental Cements for the specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5mm/min.

Type of Dental Cements		A	B
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation		3.5 13.4 0.23 0.88	4.5 13.4 0.19 0.96
Mean Strength+ Deviation Coefficient (%)		12.0 31.6	12.2 21.8
Estimated Stress+ at Failure Probability			
At 0.01%	- Weibull Normal	0.9 9.44	1.8 10.4
1%	- Weibull Normal	3.5 10.39	4.92 11.1
99.99%	- Weibull Normal	20.7 14.56	18.7 14.0

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34°C, 100% humidity prior testing.
A - Ketac Fil B - Ketac Silver

TABLE 8.3.6.1(b)

Wet Diametral Tensile strength of Ketac-Fil. Each batch of 5 specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5 mm/min.

Batch no	1	2	3	4	5	6
Data+1	15.8	14.9	7.6	10.6	16.7	18.6
Data+2	11.5	8.7	11.9	16.6	17.5	9.6
Data+3	10.7	10.5	7.4	14.1	20.7	9.3
Data+4	8.5	8.5	10.9	14.1	16.6	8.9
Data+5	7.7	12.2	8.9	7.4	9.3	20.0
Mean Strength+	10.9	11.0	9.3	12.6	16.2	13.3
Deviation Coefficient (%)	26.2	21.6	19.2	25.4	23.2	37.3
Weibull Modulus	3.9	4.8	5.4	4.1	4.5	2.7
Characteristic Strength+	12.3	12.1	10.2	18.0	18.0	15.9

(ii) Wet Diametral Tensile strength of Ketac-Sliver. Each batch of 5 specimens * of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5 mm/min.

Batch no	1	2	3	4	5	6
Data+1	13.9	15.8	16.1	13.5	11.4	10.4
Data+2	13.3	10.6	6.4	12.2	7.3	10.5
Data+3	13.7	6.8	7.2	10.6	16.6	10.2
Data+4	11.0	14.3	14.1	14.3	13.3	10.1
Data+5	14.5	15.9	11.7	6.8	10.4	6.9
Mean Strength+	13.3	12.7	11.1	11.5	11.8	9.6
Deviation Coefficient (%)	8.99	27.8	34.2	23.3	26.2	14.2
Weibull Modulus	11.8	3.7	3.0	4.4	3.9	7.4
Characteristic Strength+	13.8	14.4	13.0	12.8	13.3	10.3

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34°C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34°C , 100% humidity prior testing.

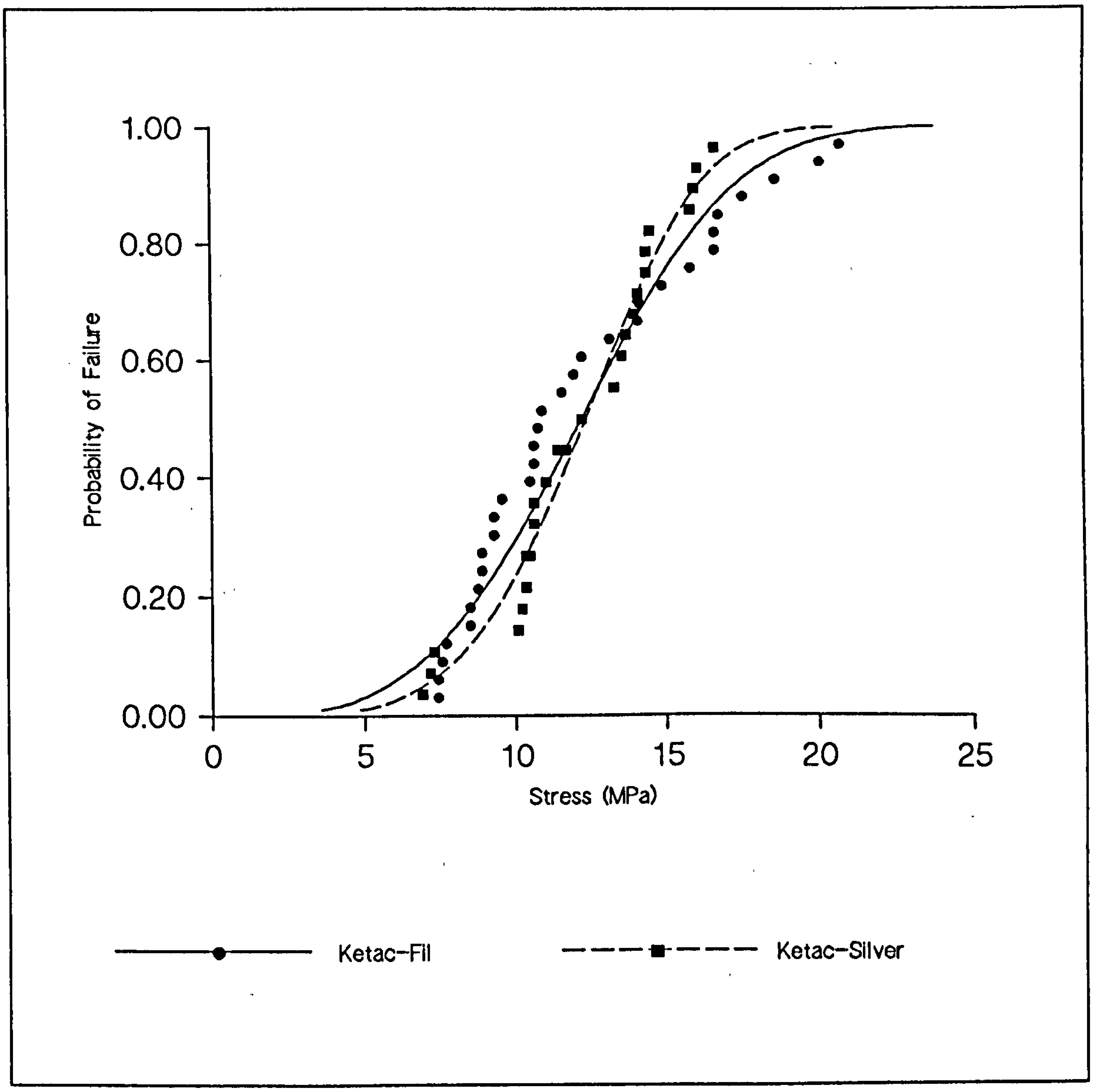


FIGURE 8.3.6.1(a)
Diametral Tensile strength of Dental Cements-Probability of failure versus diametral tensile stress for the specimens of size 4mm diameter by 3mm length which were tested at crosshead speed 0.5mm/min.

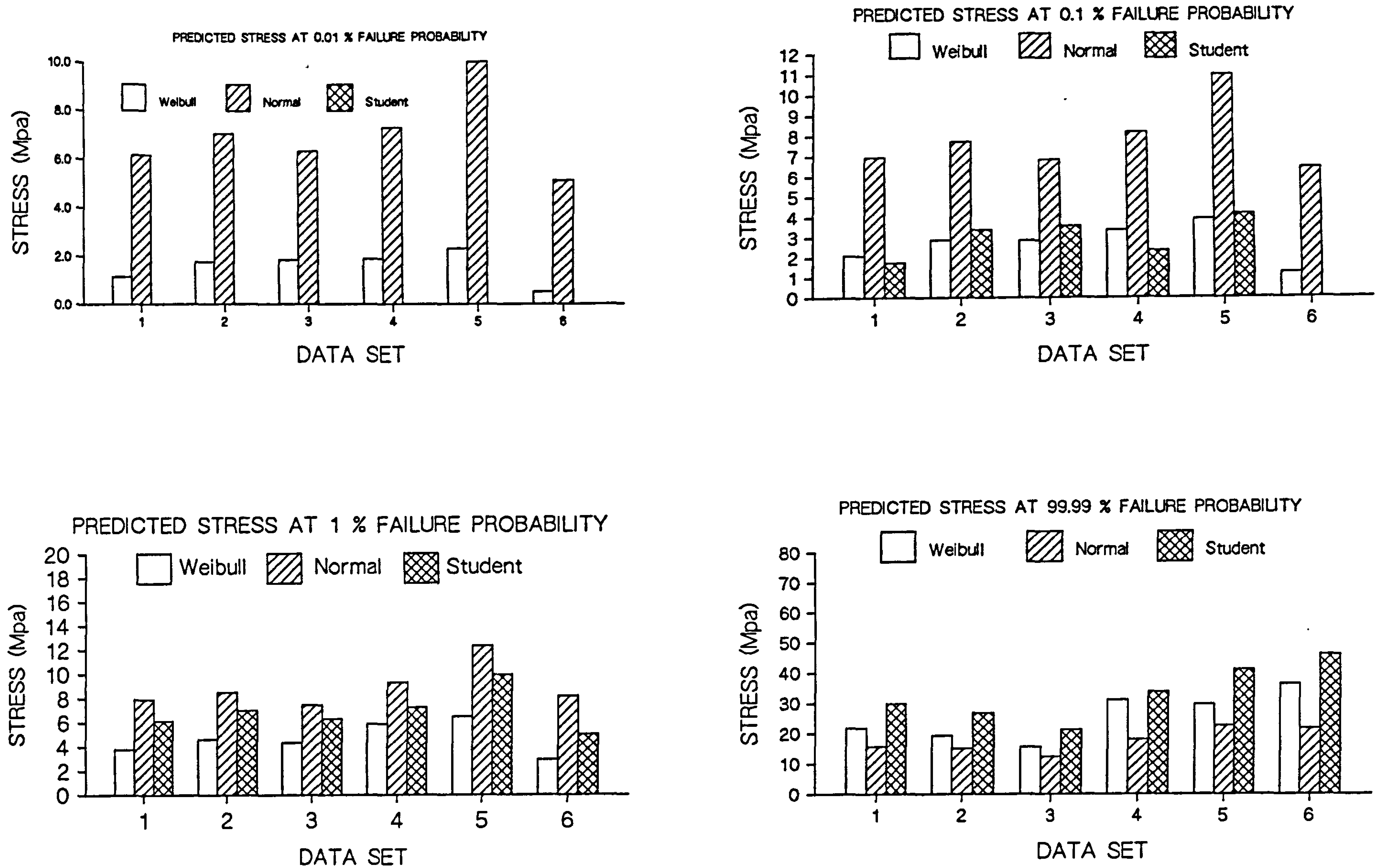


FIGURE 8.3.6.1(b) - Wet Diametral Tensile strength of Ketac-Fil. Predicted stress at various failure probability levels.

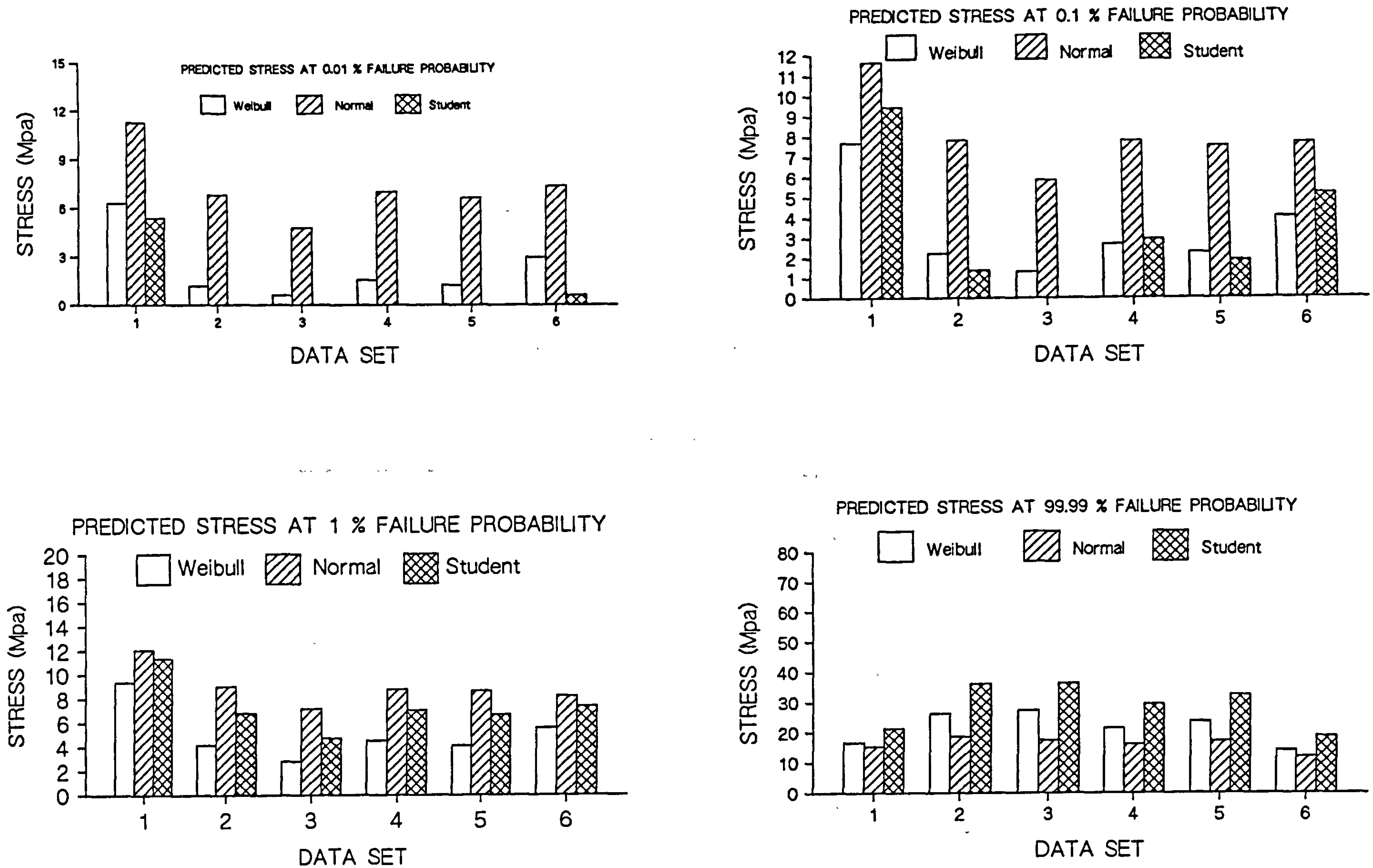


FIGURE 8.3.6.1(c) - Wet Diametral Tensile strength of Ketac-Silver. Predicted stress at various failure probability levels.

TABLE 8.3.7.1(a)

Summary of Weibull analysis-Flexural strength of Silux for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Conditions	Wet	Dry
Weibull Modulus Characteristic Strength+ Standard Error of Modulus Coeff. of Correlation	11.4 118.4 0.35 0.98	10.1 99.9 0.5 0.94
Mean Strength+ Deviation Coefficient (%)	113.4 9.5	95.3 10.4
Estimated Stress+ at Failure probability		
0.01% - Weibull Normal	52.6 106.1	40.2 88.6
1% - Weibull Normal	78.9 108.8	63.4 91.1
99.99% - Weibull Normal	135.4 120.7	116.2 102.0

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at 34^{o}C, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.

Oneway analysis of variance-Very highly significant difference between strength of the specimens stored in wet condition compared with the strength of the specimens stored in dry condition ($P < 0.001$).

TABLE 8.3.7.1(b)

(i) Wet Flexural strength of Silux for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Batch no	1	2	3	4	5
Data+1	121.9	133.1	105.9	129.3	102.2
Data+2	106.9	94.7	114.3	120.0	93.8
Data+3	108.8	111.6	96.6	124.7	112.5
Data+4	125.6	116.3	121.9	118.1	129.4
Data+5	105.0	108.8	124.7	121.9	114.4
Mean Strength+	113.6	112.9	112.7	112.8	110.4
Deviation Coefficient (%)	7.4	11.0	9.2	3.2	10.9
Weibull Modulus	14.3	9.6	11.5	34.0	9.7
Characteristic Strength+	117.7	118.8	117.6	124.8	116.2

(ii) Dry Flexural strength of Silux for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Batch no	1	2	3	4	5	6
Data+1	93.8	108.8	79.7	86.3	117.2	94.7
Data+2	106.9	95.6	89.1	89.1	109.7	98.4
Data+3	86.3	105.9	88.1	84.4	101.3	83.4
Data+4	105	94.7	101.3	79.7	105.0	90.9
Data+5	105	108.8	78.8	93.8	88.2	89.1
Mean Strength	99.4	102.8	87.4	86.6	104.3	91.3
Deviation Coefficient (%)	8.09	6.1	9.29	5.4	9.26	5.57
Weibull Modulus	13.1	17.5	11.4	19.8	11.4	19.3
Characteristic Strength	103.2	105.8	91.3	88.9	108.9	93.8

+ unit in Mpa.

* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34°C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

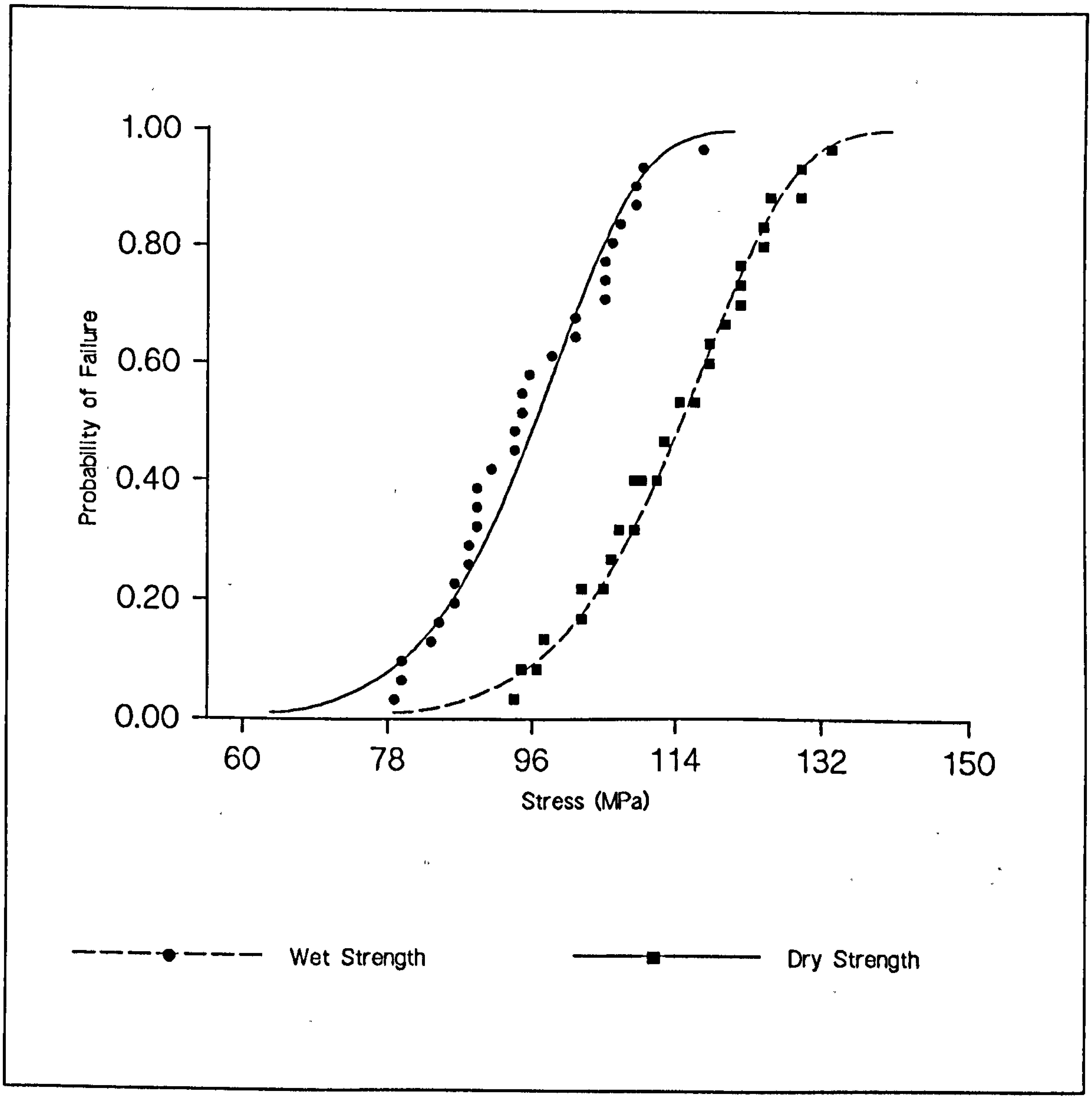


FIGURE 8.3.7.1(a)

Flexural strength of Silux-Probability of failure versus flexural stress for the specimens of size 2mm width by 2mm depth which were tested for span 20mm at crosshead speed 0.5mm/min.

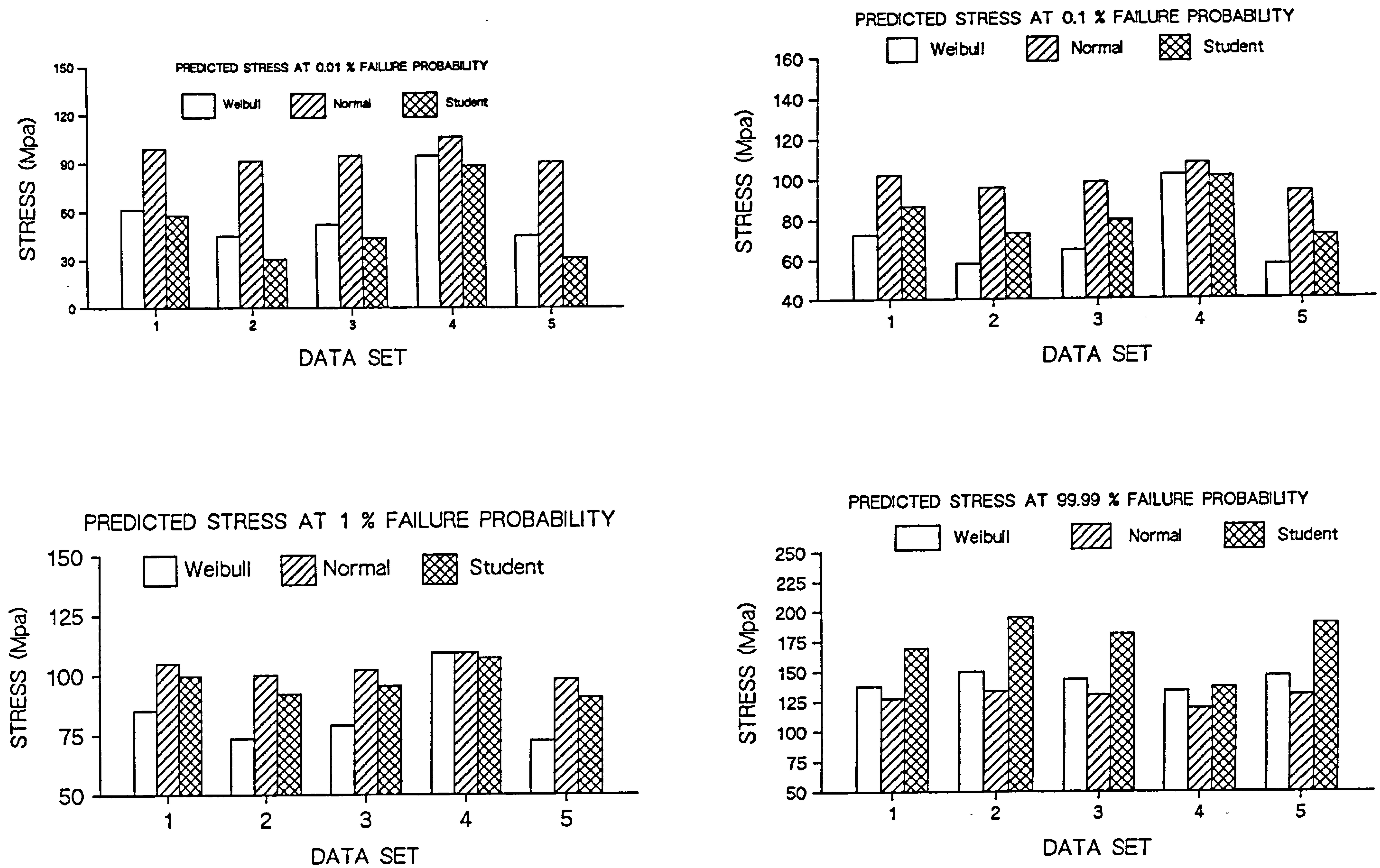


FIGURE 8.3.7.1(b) - Wet Flexural strength of Silux. Predicted stress at various failure probability levels.

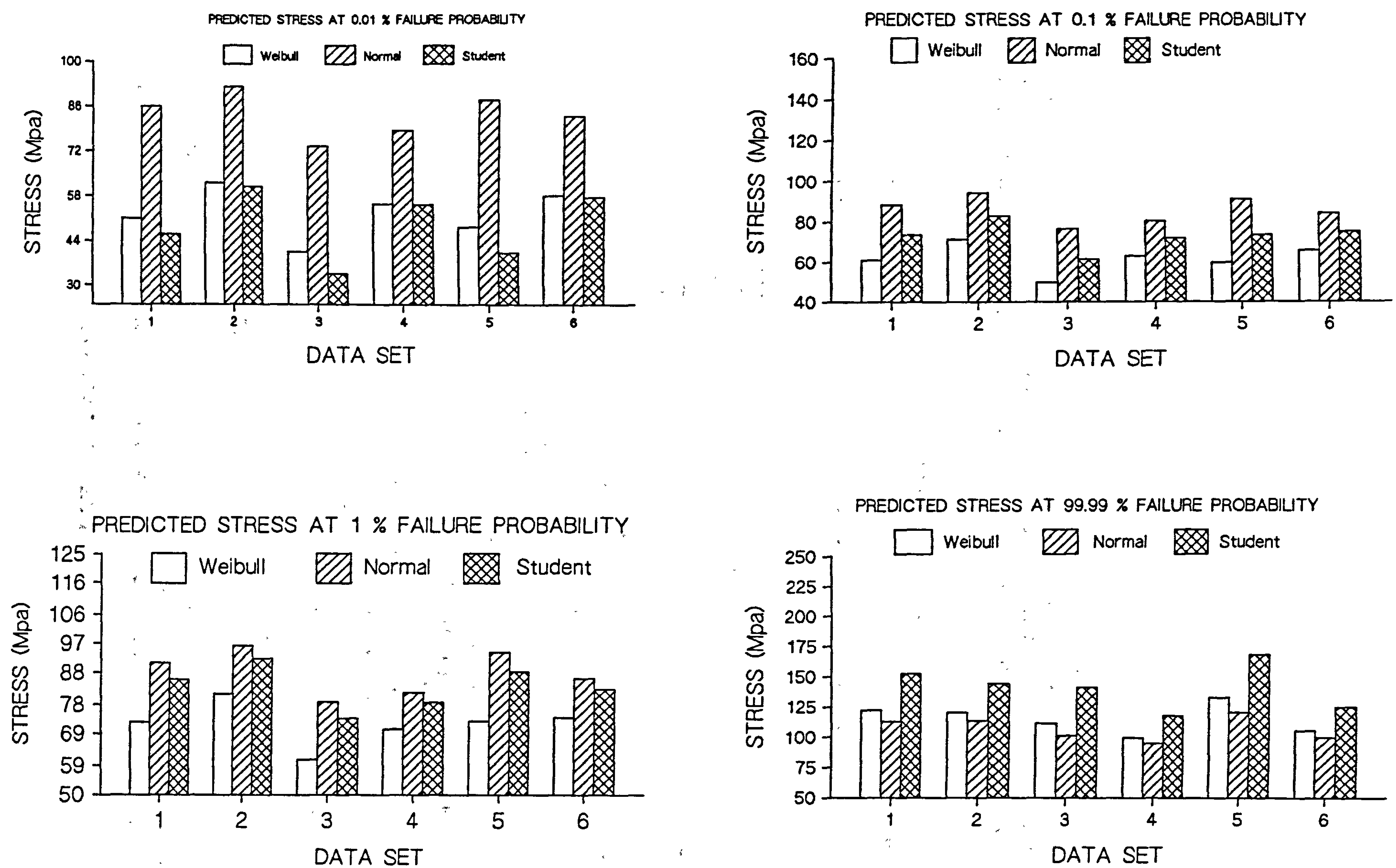


FIGURE 8.3.7.1(c) - Dry Flexural strength of Silux. Predicted stress at various failure probability levels.

TABLE 8.3.7.2(a)

Summary of Weibull analysis-Flexural strength of P50 Plus for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Conditions		Wet	Dry
Weibull Modulus		7.7	4.8
Characteristic Strength+		225.0	190.9
Standard Error of Modulus		0.24	0.1
Coeff. of Correlation		0.97	0.99
Mean Strength+		211.9	175.0
Deviation Coefficient (%)		13.8	21.9
Stress+ at Failure Probability			
0.01%	- Weibull	67.9	27.5
	Normal	192.1	149.1
1%	- Weibull	123.7	72.6
	Normal	199.5	158.7
99.99%	- Weibull	274.4	263.1
	Normal	231.7	200.9

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at 34°C, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.

Oneway analysis of variance-Very highly significant difference between strength of the specimens stored in wet condition compared with the strength of the specimens stored in dry condition ($P < 0.001$).

TABLE 8.3.7.2(b)

(i) Wet Flexural strength of P50 for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Batch no	1	2	3	4	5	6
Data+1 Data+2 Data+3 Data+4 Data+5	171.6 247.5 221.3 262.5 204.4	178.1 153.8 170.6 198.8 165.0	168.8 230.6 226.9 228.8 246.6	187.5 228.8 211.9 206.3 249.4	202.5 227.8 213.8 226.9 258.8	241.9 204.4 178.1 234.4 211.9
Mean Strength+ Deviation Coefficient (%)	221.4 14.5	173.3 8.7	220.1 12.1	216.8 9.7	225.9 8.3	214.2 10.6
Weibull Modulus Characteristic Strength+	7.2 236.9	12.2 180.4	8.7 232.8	10.9 226.8	12.7 234.9	9.9 224.9

(ii) Dry Flexural strength of P50 for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Batch no	1	2	3	4	5	6
Data+1 Data+2 Data+3 Data+4 Data+5	187.5 193.1 227.8 157.5 251.3	243.8 164.1 110.6 189.4 143.4	180.9 225.0 230.6 138.8 166.9	152.8 196.9 163.1 115.3 135.9	108.8 198.8 150.9 195.0 96.6	162.2 174.4 211.9 176.3 190.3
Mean Strength+ Deviation Coefficient (%)	203.4 16.1	170.3 26.4	188.4 18.5	152.8 17.9	150.0 28.2	183.0 9.3
Weibull Modulus Characteristic Strength+	6.5 219.3	3.9 192.9	5.6 205.5	5.8 166.1	3.6 171.5	11.4 191.1

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34°C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

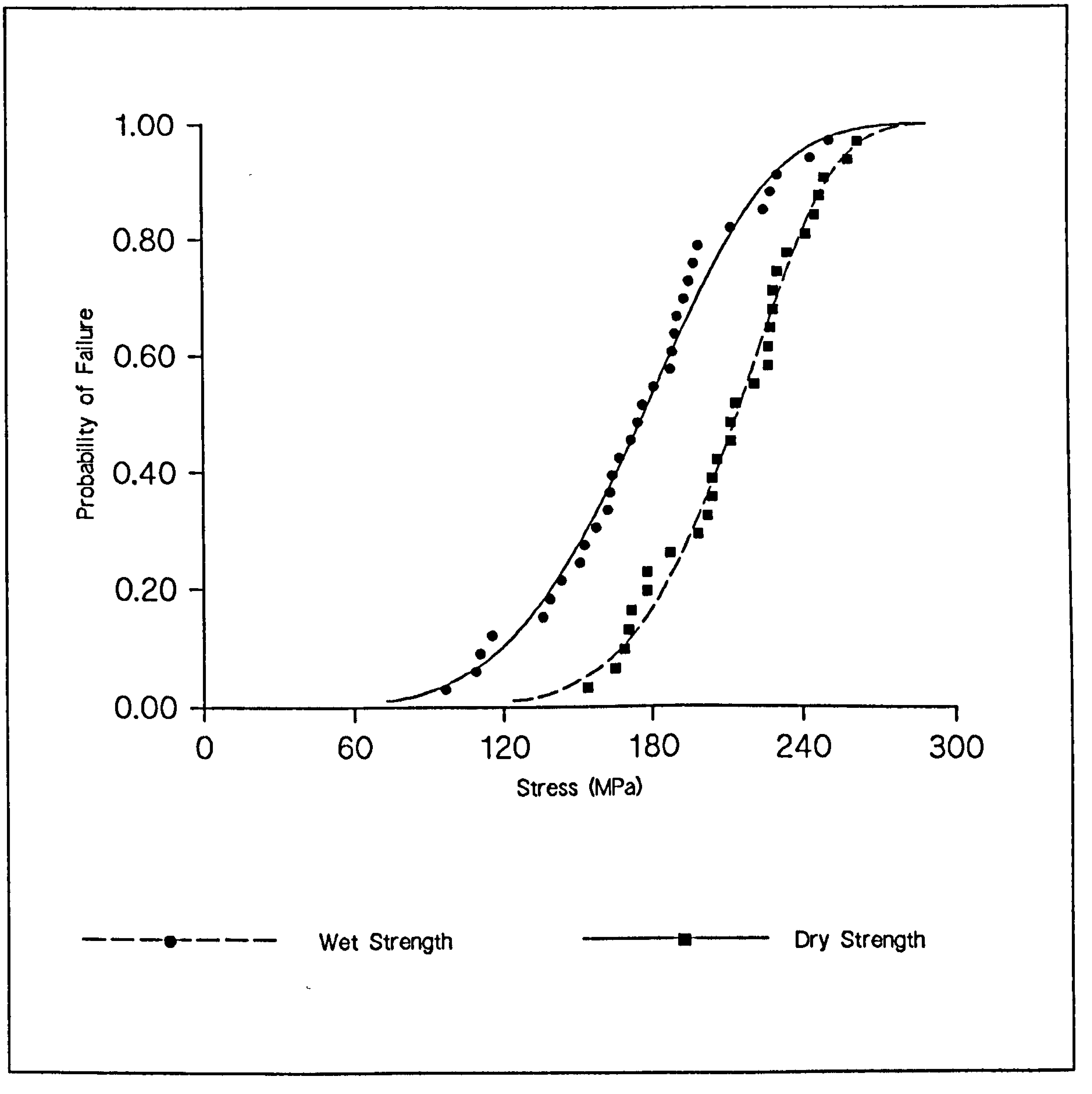


FIGURE 8.3.7.2(a)
Flexural strength of P50 Plus-Probability of failure versus flexural stress for the specimens of size 2mm width by 2mm depth which were tested for span 20mm at crosshead speed 0.5mm/min.

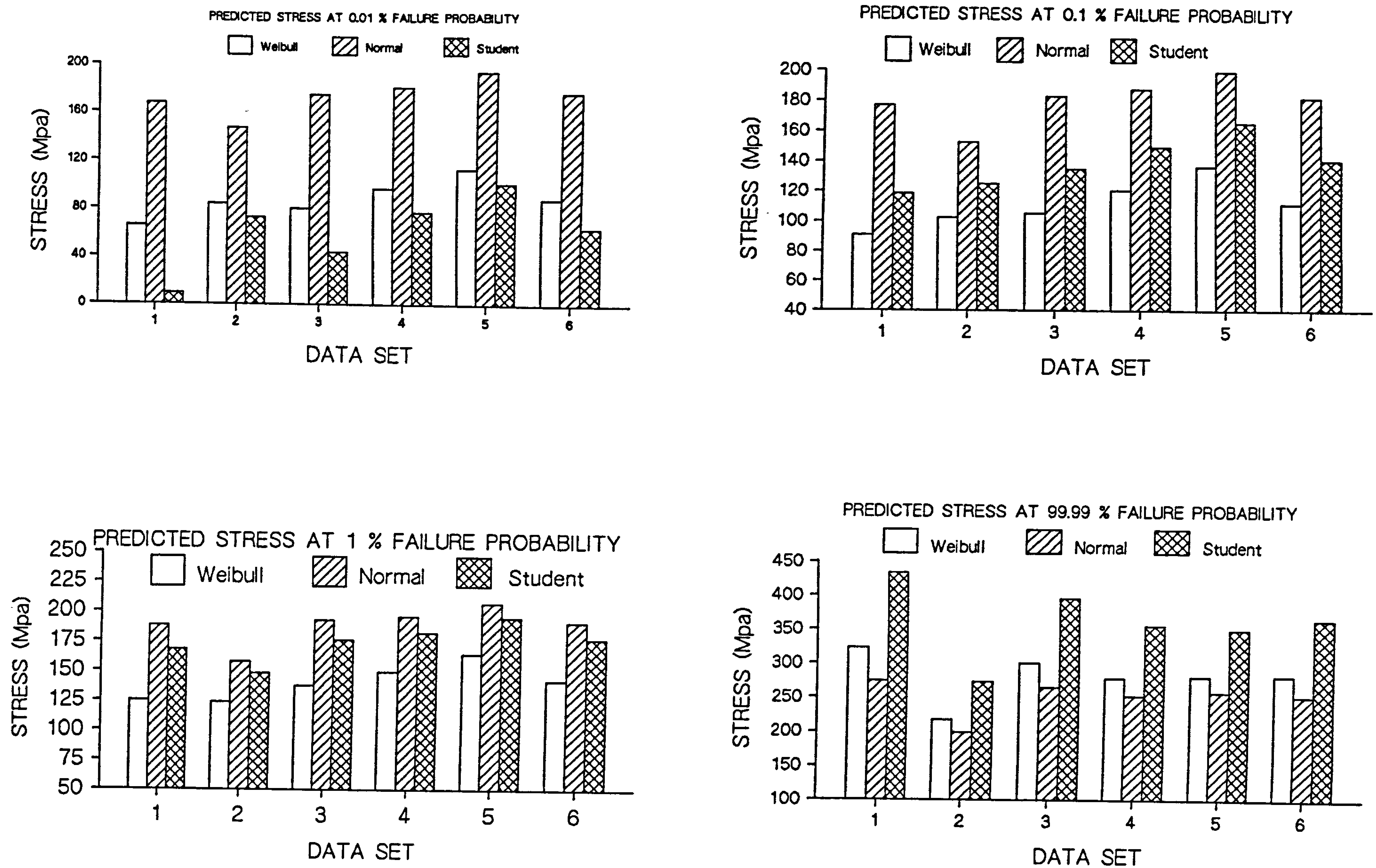


FIGURE 8.3.7.2(b) - Wet Flexural strength of P50. Predicted stress at various failure probability levels.

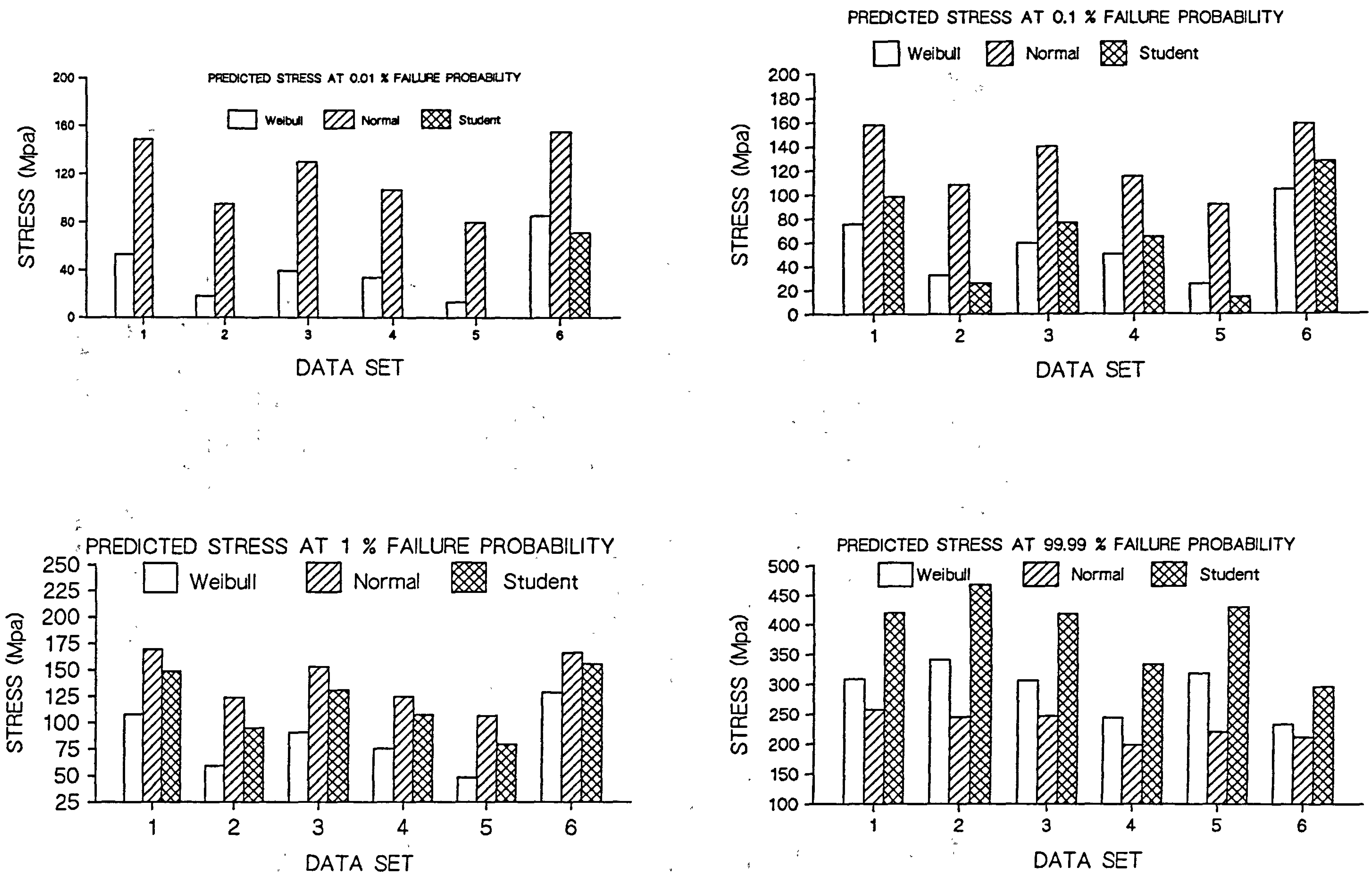


FIGURE 8.3.7.2(c) - Dry Flexural strength of P50. Predicted stress at various failure probability levels.

TABLE 8.3.8.1(a)

Summary of Weibull analysis-Flexural strength of Amalcap for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Conditions	Wet	Dry
Weibull Modulus	11.8	12.2
Characteristic Strength+	119.4	128.3
Standard Error of Modulus	0.46	0.47
Coeff. of Correlation	0.97	0.95
Mean Strength+	114.7	123.2
Deviation Coefficient (%)	9.0	9.0
Stress+ at Failure Probability		
0.01% - Weibull	54.9	60.2
Normal	107.7	115.7
1% - Weibull	81.0	87.9
Normal	110.3	118.5
99.99% - Weibull	135.9	145.5
Normal	121.7	130.7

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at 34°C, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.

Oneway analysis of variance - Highly significant difference between the strength of the specimens stored in wet condition compared with the strength of the specimens stored in dry condition ($P<0.05$).

TABLE 8.3.8.1(b

(i) Wet Flexural strength of Amalcap for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Batch no	1	2	3	4	5
Data+1 Data+2 Data+3 Data+4 Data+5	118.1 110.6 131.3 131.3 105.0	131.3 123.8 93.6 105.0 105.0	166.3 123.8 112.5 118.1 110.6	103.1 99.4 116.3 112.5 97.5	121.9 118.1 116.3 114.4 129.4
Mean Strength+ Deviation Coefficient (%)	119.3 8.9	112.1 11.8	116.3 3.9	105.8 7.0	120.0 4.4
Weibull Modulus Characteristic Strength+	11.9 124.3	8.9 118.5	27.4 118.5	15.3 109.3	24.4 122.6

(ii) Dry Flexural strength of Amalcap for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Batch no	1	2	3	4	5	6
Data+1 Data+2 Data+3 Data+4 Data+5	118.1 127.5 125.6 106.9 125.6	127.5 118.1 131.3 134.1 133.1	120.0 112.5 149.1 118.1 108.8	125.6 103.1 123.8 129.4 110.6	118.1 129.4 118.1 120.0 129.4	121.9 126.6 134.1 106.9 141.6
Mean Strength+ Deviation Coefficient (%)	120.8 6.3	128.8 4.5	121.7 11.7	118.5 8.4	123.0 4.3	126.2 9.3
Weibull Modulus Characteristic Strength+	16.9 124.4	24.0 131.6	9.0 128.5	12.6 123.3	25.3 125.6	11.4 131.8

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34^{o}C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

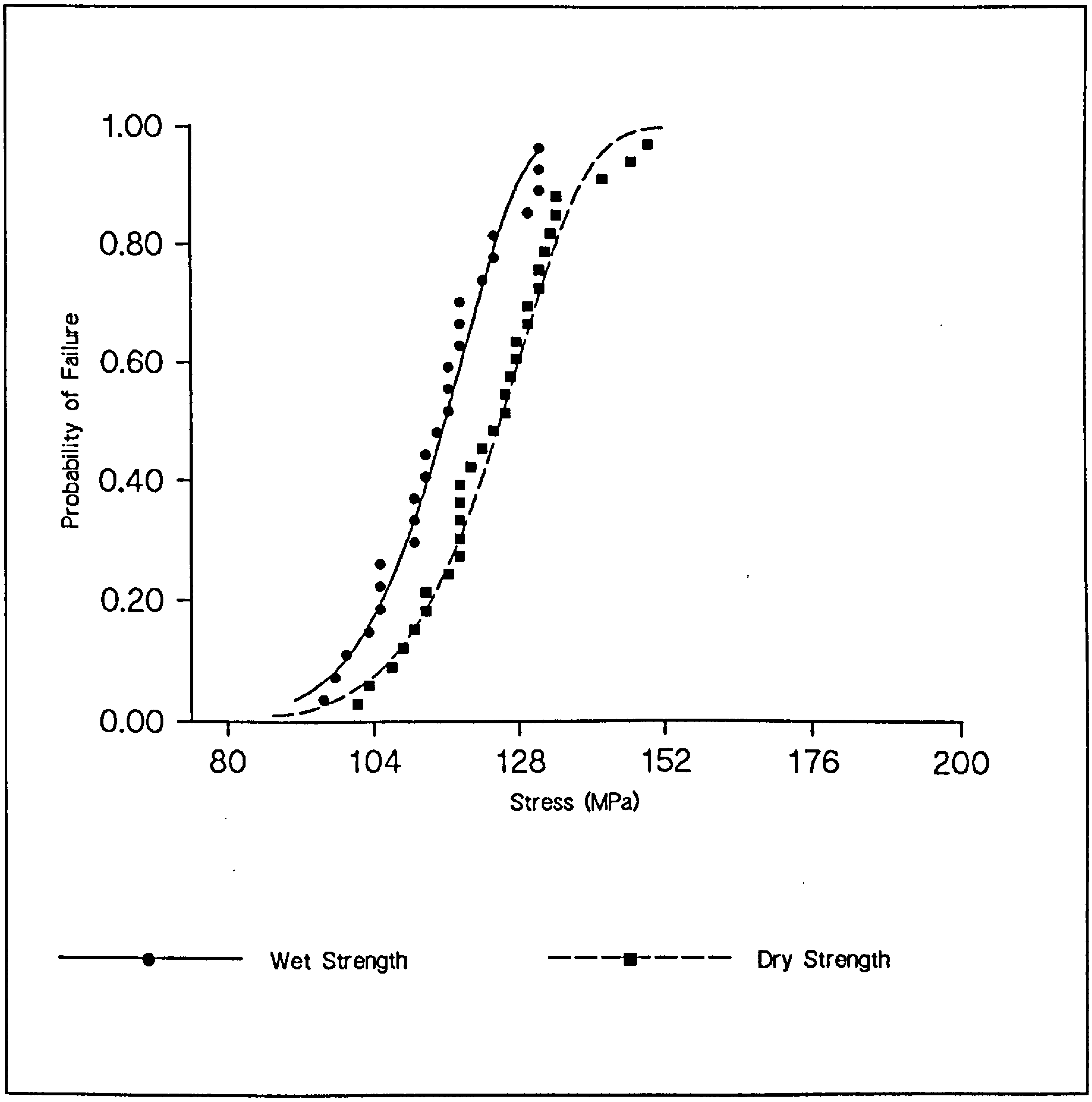


FIGURE 8.3.8.1(a)
Flexural strength of Amalcap-Probability of failure versus flexural stress for the specimens of size 2mm width by 2mm depth which were tested for span 20mm at crosshead speed 0.5mm/min.

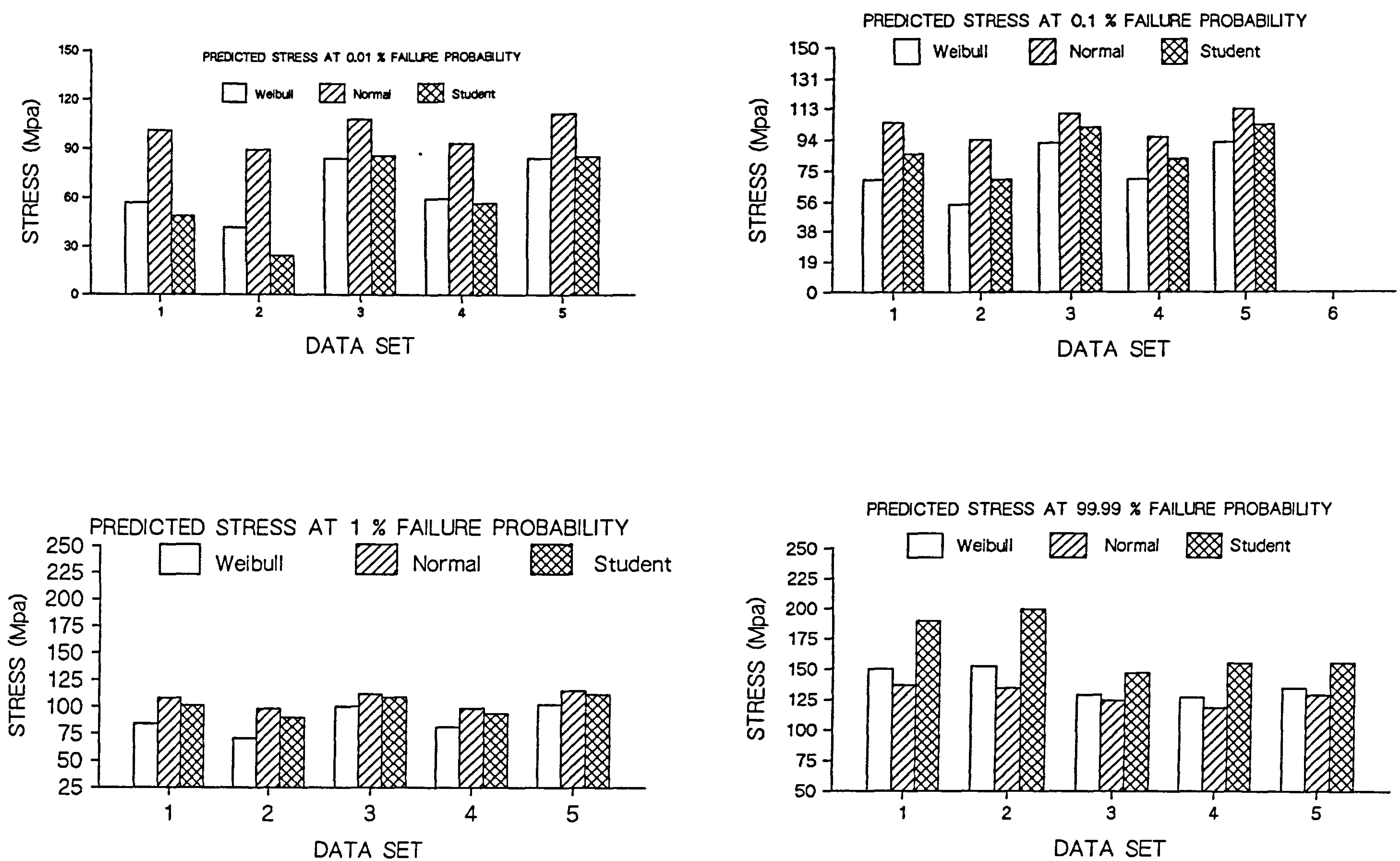


FIGURE 8.3.8.1(b) - Wet Flexural strength of Amalcap. Predicted stress at various failure probability levels.

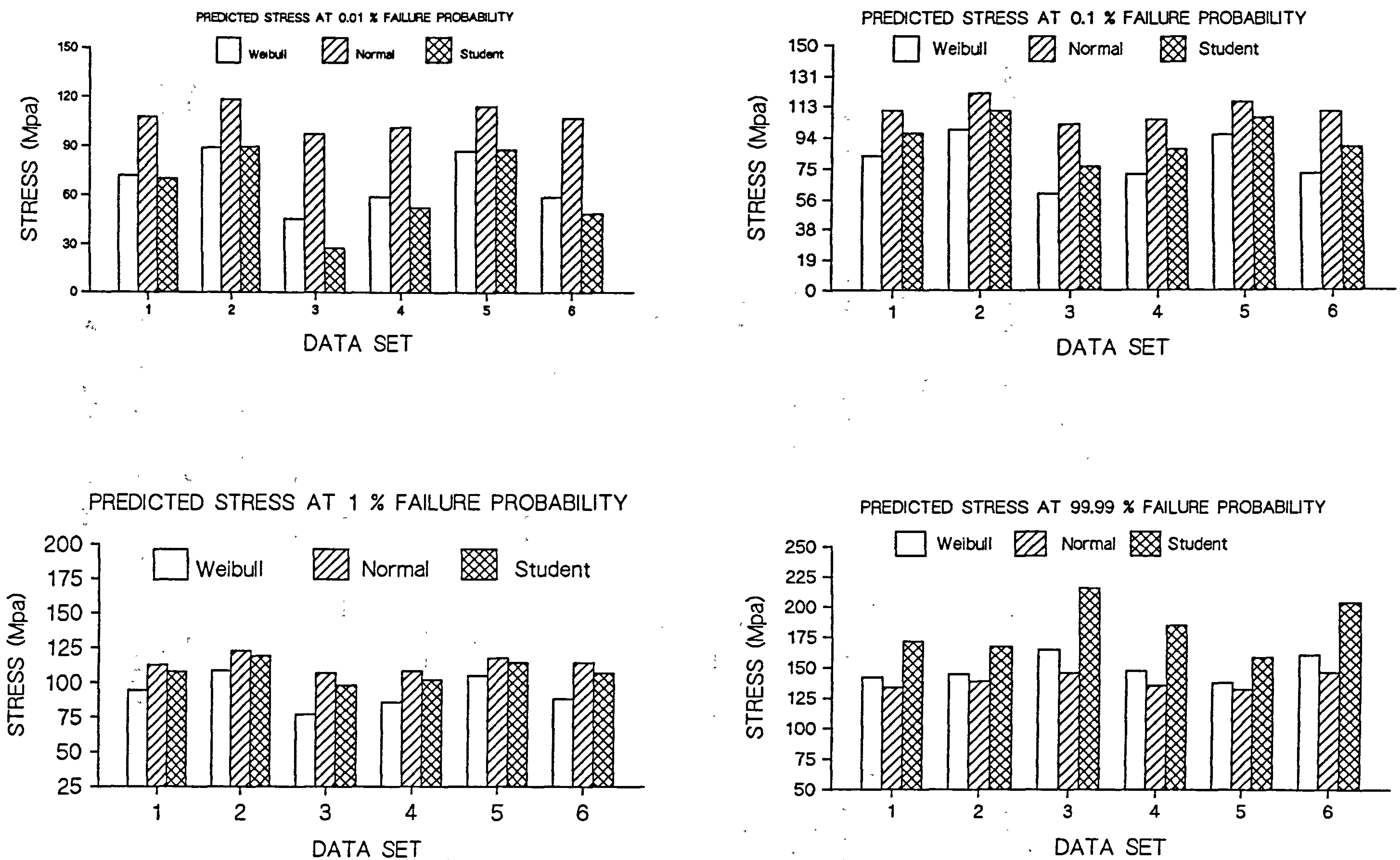


FIGURE 8.3.8.1(c) -Dry Flexural strength of Amalcap. Predicted stress at various failure probability levels.

TABLE 8.3.8.2(a)

Summary of Weibull analysis-Flexural strength of Dispersalloy for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Conditions	Wet	Dry
Weibull Modulus	5.7	13.3
Characteristic Strength+	133.3	146.4
Standard Error of Modulus	0.22	0.46
Coeff. of Correlation	0.96	0.96
Mean Strength+	123.4	141.1
Deviation Coefficient (%)	17.2	8.2
Stress+ at Failure Probability		
0.01% - Weibull	26.2	73.4
0.01% - Normal	109.1	133.3
1% - Weibull	39.3	103.7
1% - Normal	114.4	136.2
99.99% - Weibull	174.7	164.2
99.99% - Normal	137.7	148.9

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in wet and dry conditions. Wet: Specimens were store in distilled water for 7 days at 34°C, 100% humidity prior testing. Dry: Specimens were bench dried for 7 days prior testing.

Oneway analysis of variance - Very highly significant difference between the strength of the specimens stored in wet condition compared with the strength of the specimens stored in dry condition ($P<0.001$).

TABLE 8.3.8.2(b)

(i) Wet Flexural strength of Dispersalloy for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Batch no	1	2	3	4	5	6
Data+1 Data+2 Data+3 Data+4 Data+5	101.3 99.4 142.5 127.5 116.3	131.3 93.8 144.4 112.5 106.9	101.3 131.3 129.4 129.4 118.1	135.0 99.4 146.3 63.8 138.8	129.4 78.8 112.5 120.0 144.4	142.5 145.3 150.9 150.9 143.4
Mean Strength+ Deviation Coefficient (%)	117.4 13.8	117.8 15.3	121.9 9.3	116.6 26.6	117.0 18.7	146.6 2.5
Weibull Modulus Characteristic Strength+	7.6 125.2	6.8 126.4	11.4 127.3	3.9 132.3	5.6 127.7	44.3 148.5

(ii) Dry *Flexural strength of Dispersalloy for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Batch no	1	2	3	4	5	6
Data+1 Data+2 Data+3 Data+4 Data+5	157.5 133.1 146.3 146.3 153.8	127.5 121.9 150.9 161.3 138.8	138.8 138.8 139.8 119.1 148.1	150.0 129.4 150.9 125.6 146.3	141.6 153.8 129.4 126.9 142.5	151.9 132.2 133.1 132.2 154.7
Mean Strength+ Deviation Coefficient (%)	147.4 5.7	140.1 10.4	136.9 7.0	140.4 7.7	140.8 5.7	140.8 7.3
Weibull Modulus Characteristic Strength+	18.9 151.4	10.2 147.0	15.2 141.5	13.9 145.6	19.0 144.6	14.7 145.7

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34°C , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and were bench dried for 7 days prior testing.

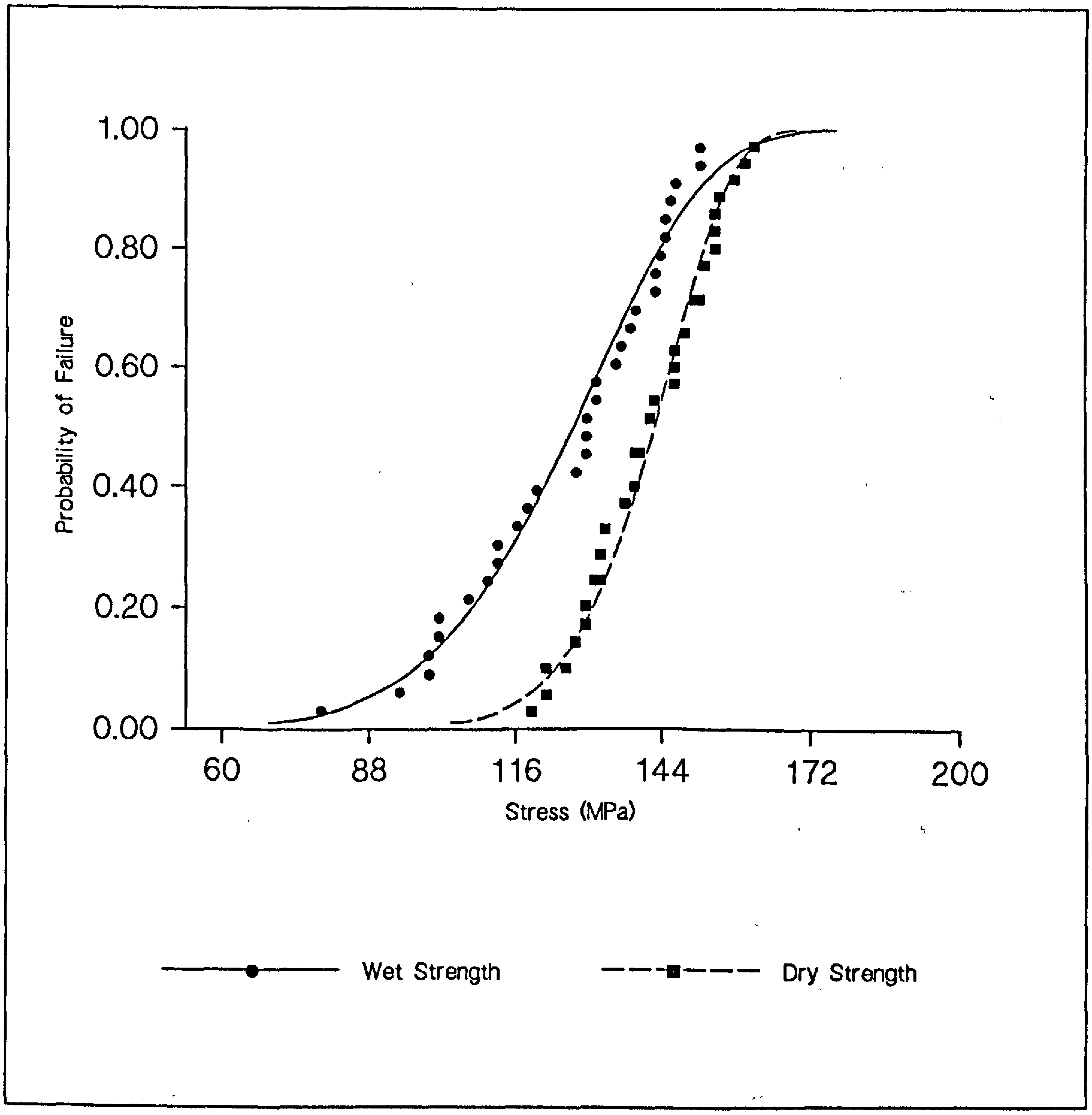


FIGURE 8.3.8.2(a)
Flexural strength of Dispersalloy - Probability of failure versus flexural stress for the specimens of size 2mm width by 2mm depth which were tested for span 20mm at crosshead speed 0.5mm/min.

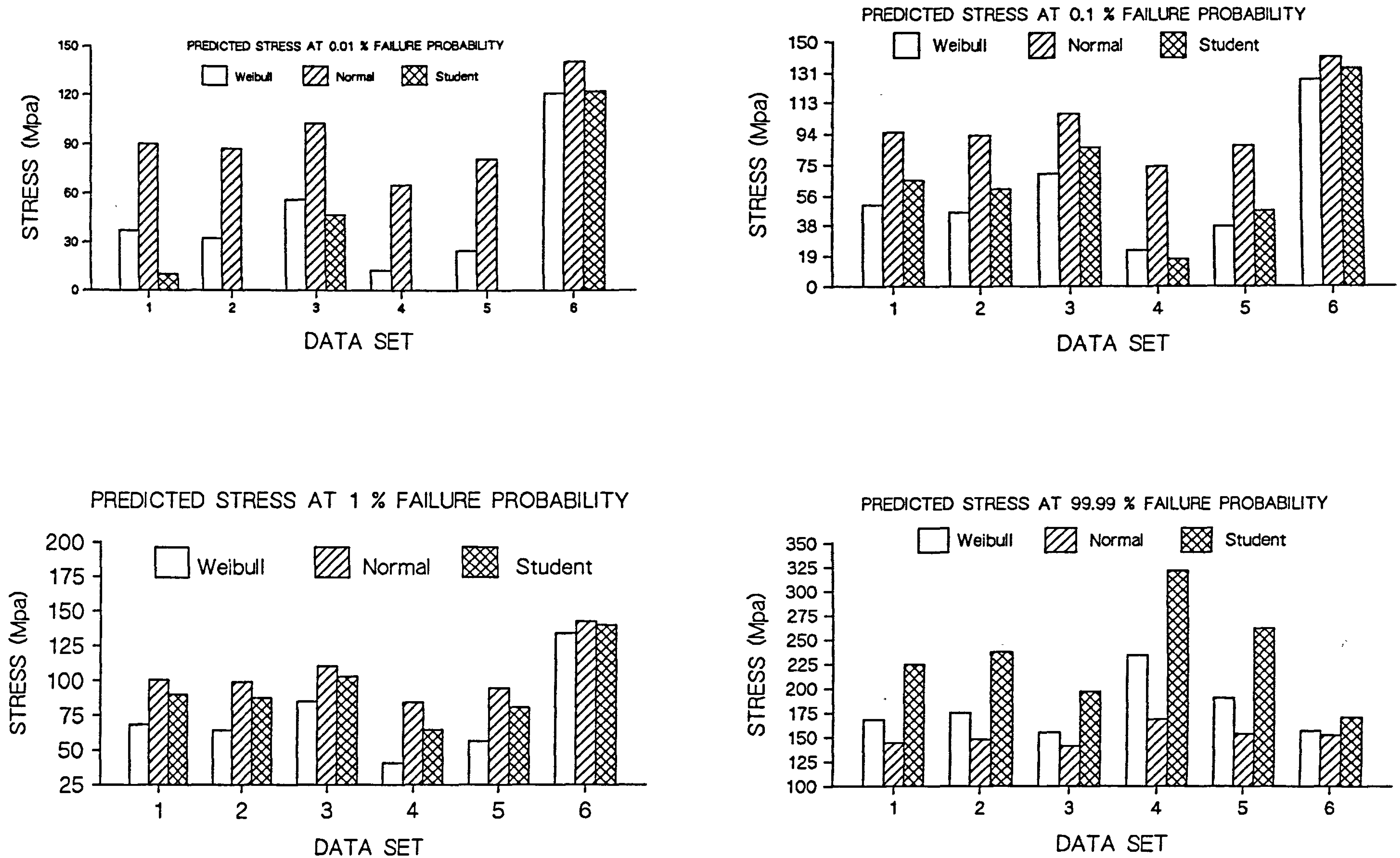


FIGURE 8.3.8.2(b) - Wet Flexural strength of Dispersalloy. Predicted stress at various failure probability levels.

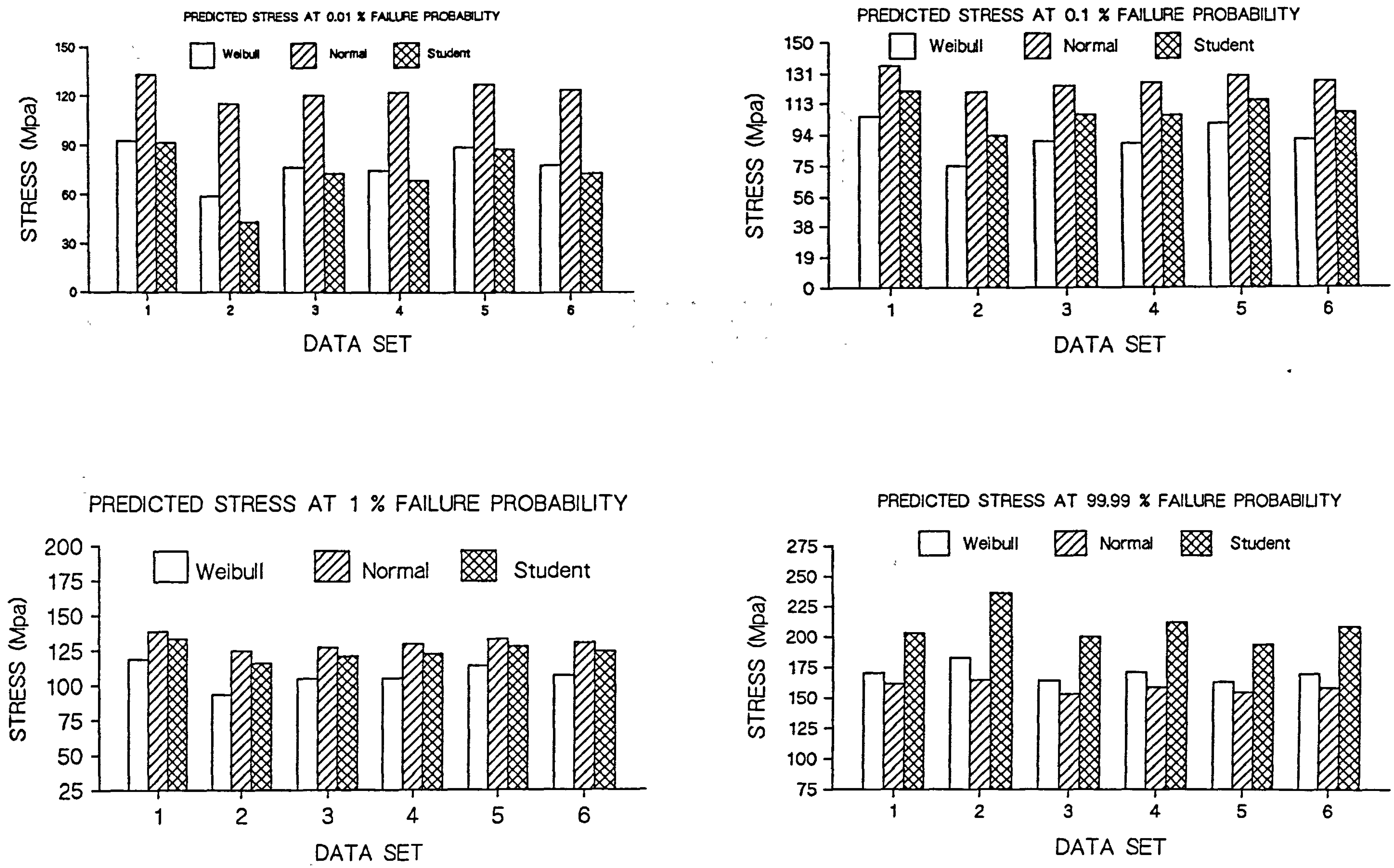


FIGURE 8.3.8.2(c) - Dry Flexural strength of Dispersalloy. Predicted stress at various failure probability levels.

TABLE 8.3.9.1(a)

Summary of Weibull analysis-Flexural strength of Dental Cements for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Type of Dental Cements	A	B
Weibull Modulus	6.0	7.2
Characteristic Strength+	35.7	42.7
Standard Error of Modulus	0.23	0.49
Coeff. of Correlation	0.96	0.88
Mean Strength+	33.2	40.01
Deviation Coefficient (%)	17.6	15.0
Stress+ at Failure Probability		
0.01% - Weibull	7.6	11.9
Normal	29.3	36.0
1% - Weibull	16.6	22.6
Normal	30.7	37.4
99.99% - Weibull	46.0	52.7
Normal	37.1	44.1

+ unit in Mpa.
* Specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34°C, 100% humidity prior testing.
A - Ketac Fil   B - Ketac Silver

TABLE 8.3.9.1(b)

(i) Wet Flexural strength of Ketac-Fil for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Batch no	1	2	3	4	5	6
Data+1	30.0	18.8	46.5	37.1	32.3	31.9
Data+2	30.0	33.8	40.9	46.5	31.9	29.3
Data+3	33.8	34.9	39.8	38.3	31.5	33.0
Data+4	28.1	29.3	39.0	36.4	27.8	31.1
Data+5	24.4	36.4	34.5	33.4	24.4	30.4
Mean Strength+	29.3	30.6	40.1	38.3	29.6	31.1
Deviation Coefficient (%)	10.4	20.9	9.6	11.5	10.3	4.1
Weibull Modulus	10.1	5.0	11.0	9.2	10.2	26.4
Characteristic Strength+	30.7	33.7	42.0	40.4	31.0	31.8

(ii) Wet Flexural strength of Ketac-Silver for the specimens * of size 2mm width by 2mm depth which were tested for 20mm span at crosshead speed 0.5mm/min.

Batch no	1	2	3	4	5	6
Data+1	52.5	41.6	39.4	36.8	46.1	40.9
Data+2	48.8	36.0	33.4	43.1	35.6	44.3
Data+3	56.3	34.9	36.4	38.3	42.4	42.8
Data+4	48.8	34.9	33.0	37.1	35.6	37.1
Data+5	40.1	37.5	37.9	34.5	41.3	49.5
Mean Strength+	49.3	36.9	36.0	37.9	40.2	42.9
Deviation Coefficient (%)	10.9	6.8	6.9	7.5	10.1	9.5
Weibull Modulus	9.7	15.7	15.4	14.1	10.4	11.1
Characteristic Strength+	51.8	38.2	37.2	39.3	42.1	44.8

+ unit in Mpa.
* Wet specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34^oC , 100% humidity prior testing. Dry specimens were prepared in a plastic mould and stored in distilled water for 7 days at 34^oC , 100% humidity prior testing.

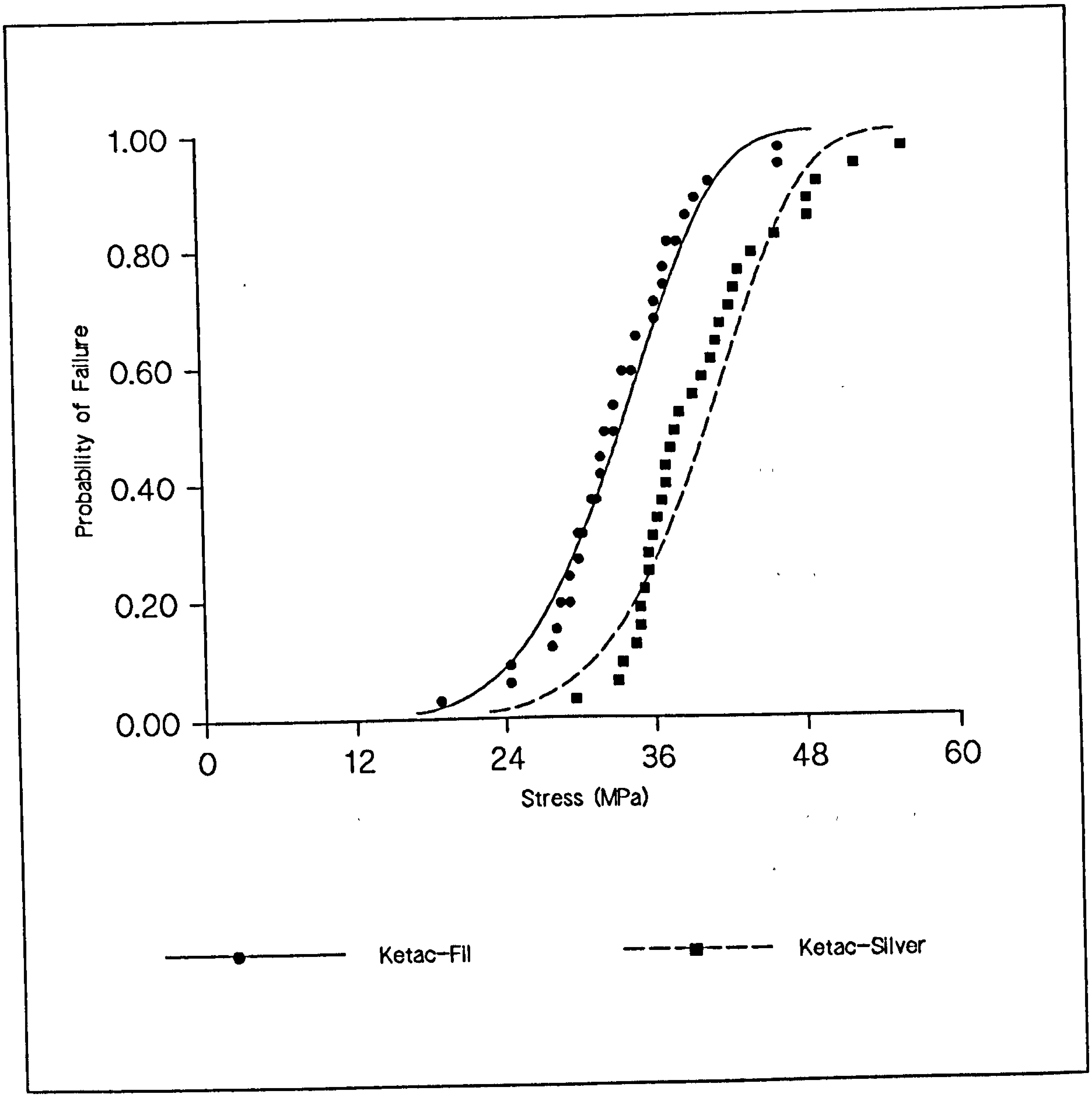


FIGURE 8.3.9.1(a)

Flexural strength of Dental Cements-Probability of failure versus flexural stress for the specimens of size 2mm width by 2mm depth which were tested for span 20mm at crosshead speed 0.5mm/min.

Specimens are stored in distill water for 7 days at 34°C, 100% humidity prior testing .

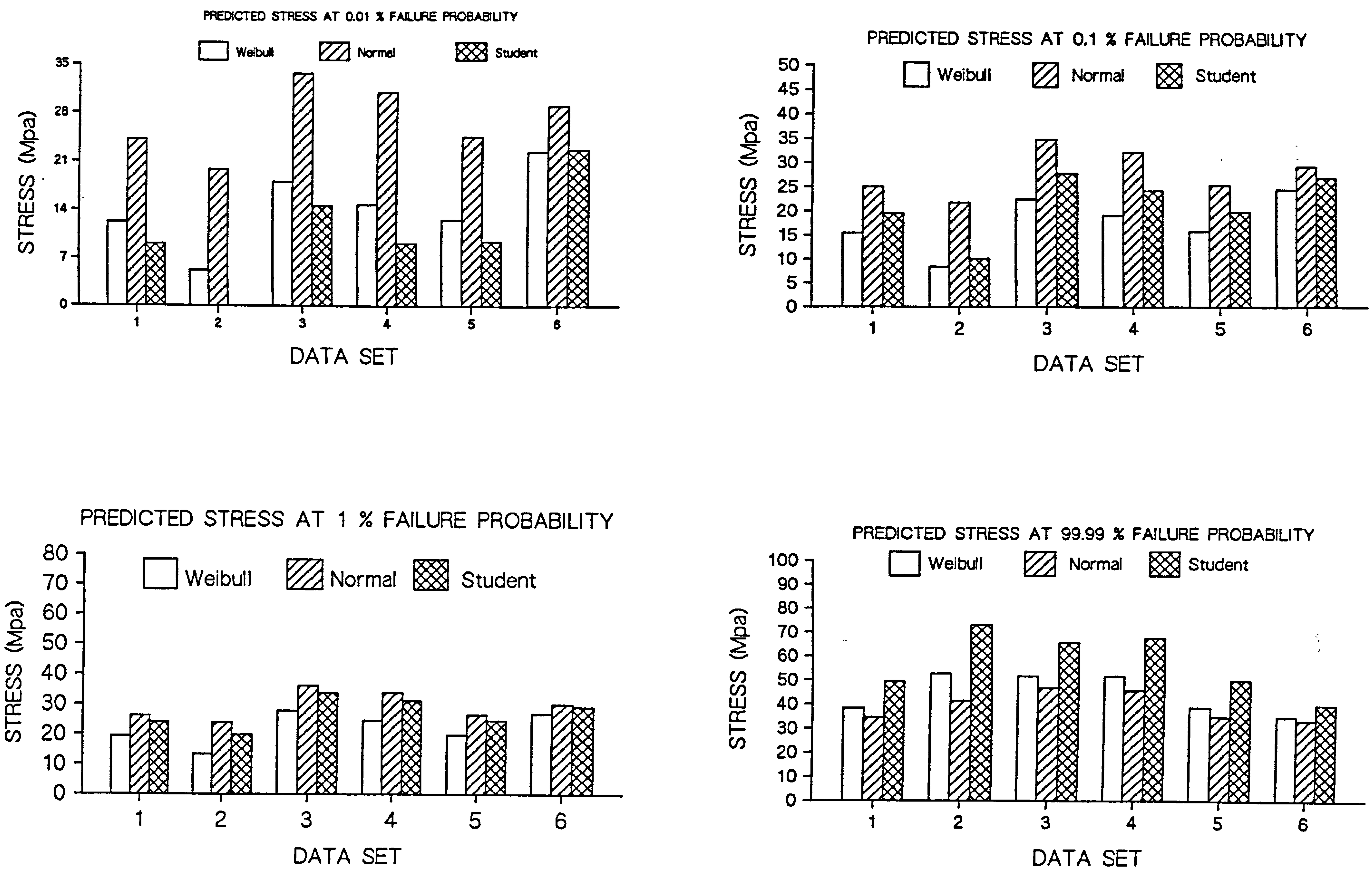
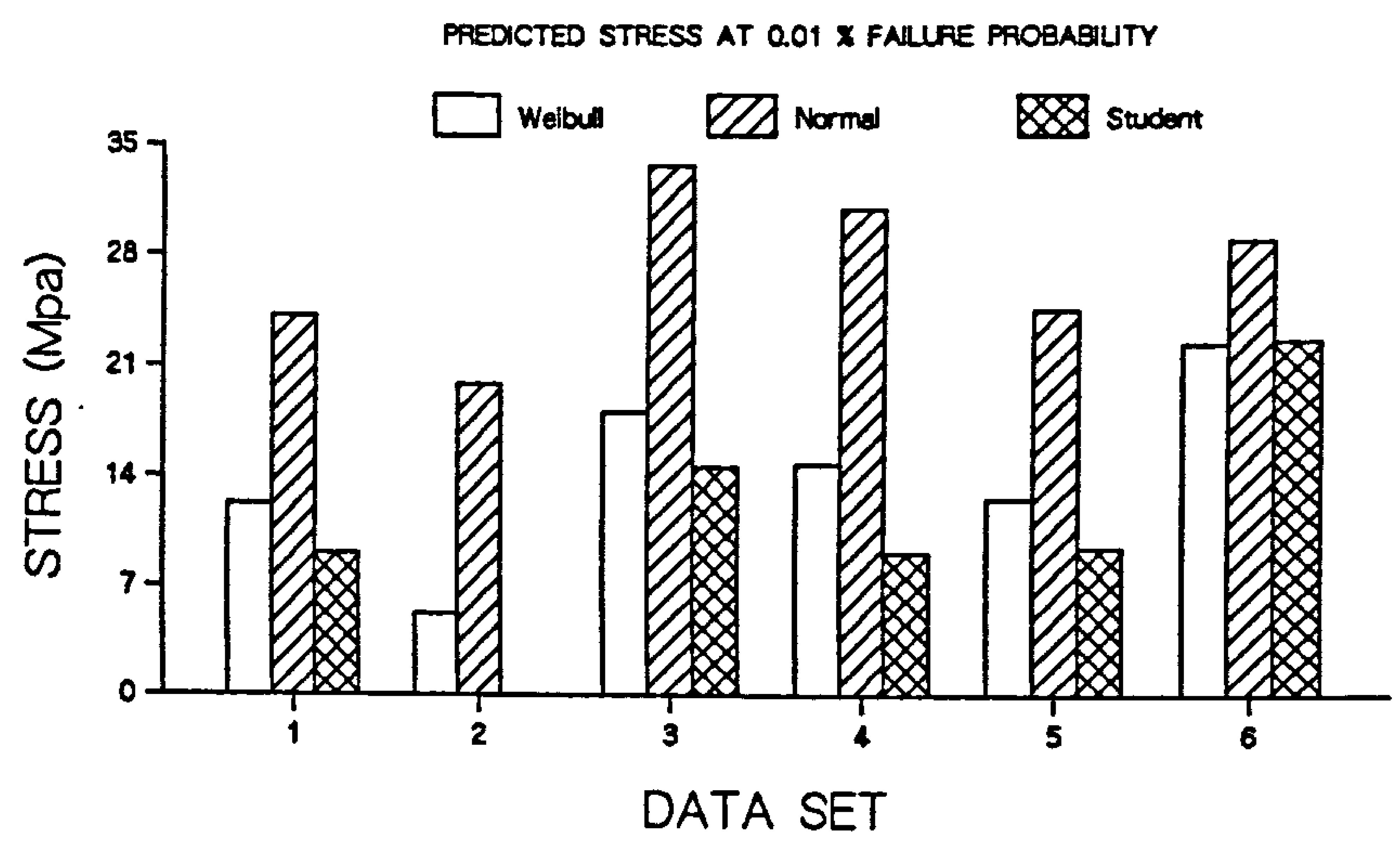
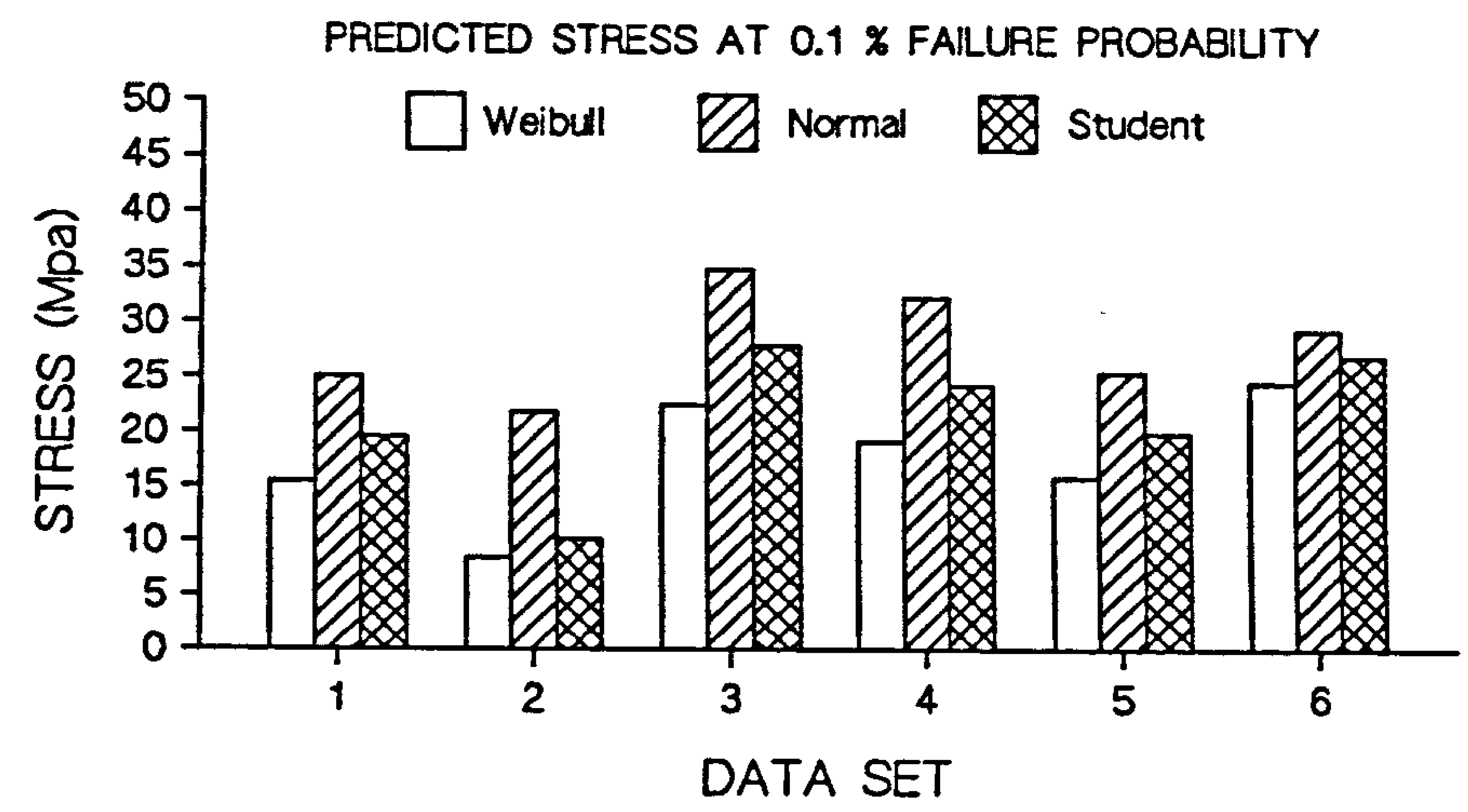
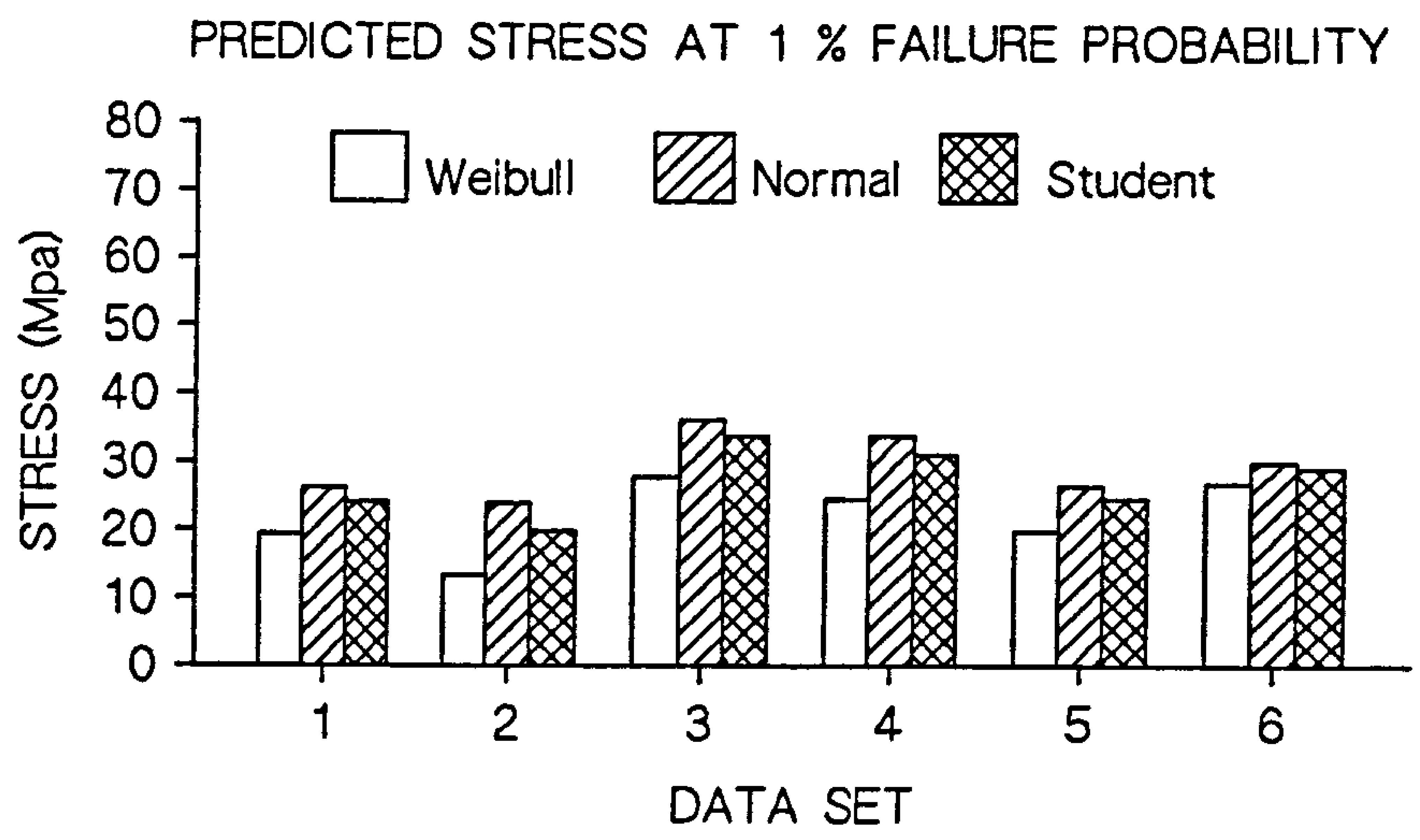


FIGURE 8.3.9.1(b) - Wet Flexural strength of Ketac-Fil. Predicted stress at various failure probability levels.







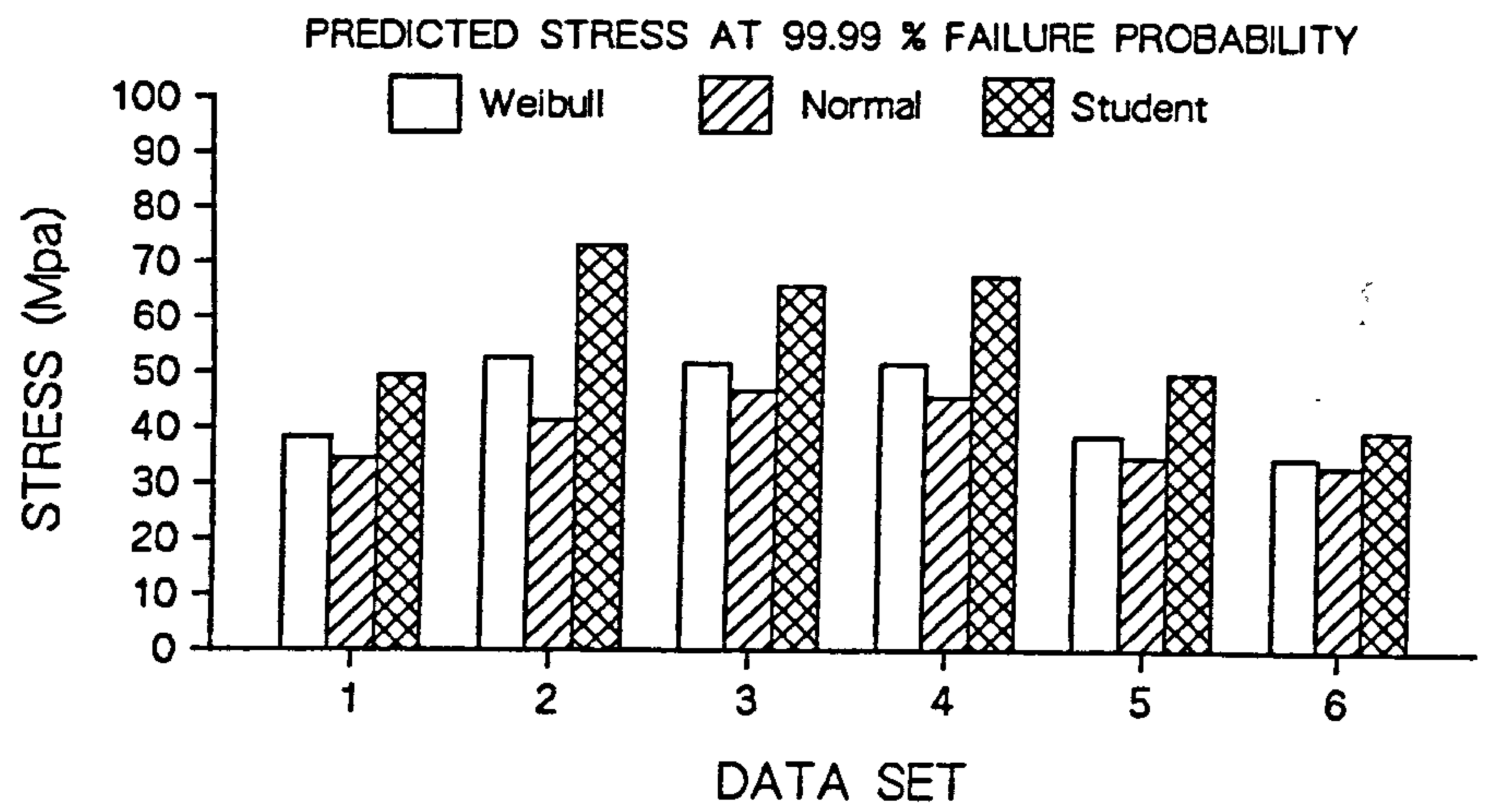


FIGURE 8.3.9.1(b) - Wet Flexural strength of Ketac-Fil. Predicted stress at various failure probability levels.

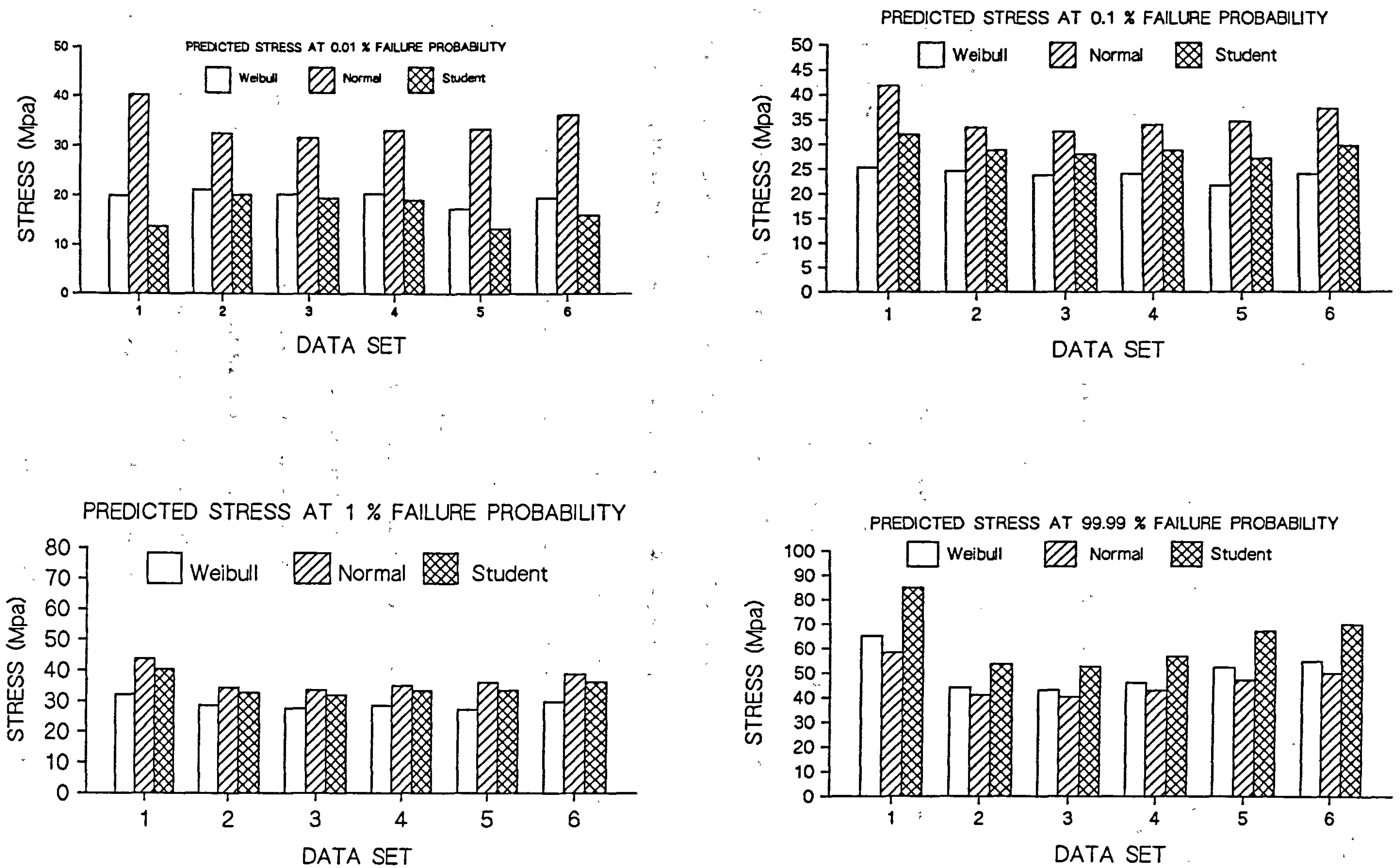


FIGURE 8.3.9.1(c) - Wet Flexural strength of Ketac-Silver. Predicted stress at various failure probability levels.

There was a highly significant difference between the 'wet' and 'dry' compressive strength of Occlusin [$P<0.001$]. This showed that storage conditions affected the compressive strength of Occlusin. The variation between the compressive strength of 'wet' and 'dry' specimens may be due to the effect of water on the dimethacrylate molecules. Some of these molecules remain unreacted (Ruyther and Svendsen:1978, Asmussen:1982, Ruyther and Oysaed:1982) and may lower the crosslink density of the polymer. When the specimens have been stored in distilled water for 7 days prior testing, some of the uncured dimethacrylate molecules may be degraded by water (Braden and Causton:1973, Braden, Causton and Clarke:1976) and this may lead to a weak network in the system. It is expected that the strength of the 'wet' Occlusin is lower than the strength of the 'dry' Occlusin but this is not the case. Figure 8.3.1.1(a) shows the compressive strength of the 'wet' Occlusin is higher than the compressive strength of the 'dry' Occlusin. However Table 8.3.1.1(a) shows, the value of Weibull modulus for the 'dry' Occlusin is less than the value of Weibull modulus of the 'wet' Occlusin. This shows that 'dry' Occlusin is more brittle than 'wet' Occlusin. It can be stated that the degree of degradation of the dimethacrylate molecules was not high enough to weaken the structure of the polymer. Therefore the high compressive strength of 'wet' Occlusin may be due to the plastic deformation. Local elastic and plastic deformation may be developed before failure for some polymeric materials (Darvell:1990). The failure may not be because of the most critical flaw has been initiated. The failure may be due to the progressive damage (Bever:1986). This can be explained by 'bundle failure' i.e in a bundle of fibers, the first fiber failure does not ordinarily cause failure in the bundle as a whole. The failure is the result of damage accumulation (Daniels 1945, Rosen:1964 - see Fiber Bundles: Strength Statistics).

There was no significant difference between the 'wet' and 'dry' compressive strength of Silux [P>0.05] and between the 'wet' and 'dry' compressive strength of P50 [P>0.05]. This showed that storage conditions do not affected the compressive strength of Silux and P50. This effect also can be seen from Figure 8.3.1.2(a) and Figure 8.3.1.3(a), where the Weibull curve for 'wet' and 'dry' specimens are close to each other. However Table 8.3.1.2(a) shows that the values of Weibull moduli of the 'wet' and 'dry' Silux are different (i.e the 'dry' Silux is more brittle than 'wet' Silux). Although the 'dry' Silux is more brittle than the 'wet' Silux, their characteristic strengths are approximately the same. This suggests that the 'wet' Silux is more reliable than the 'dry' Silux. The values Weibull moduli of the 'dry' and 'wet' P50 are approximately the same (Table 8.3.1.3(a)). The characteristic compressive strength of the 'wet' and 'dry' P50 are also approximately the same. This shows that the degradation of the constituents of P50 is not significant enough to affect the compressive strength of P50.

The above paragraphs show the effect of storage condition on the strength and properties of some of the polymeric materials. It is important for the test to replicate the environment ~~enviroment~~ of the material in service. Therefore the laboratory test should, as close as possible, reproduce the oral environment, so that the test is more realistic.

The 'wet' mean and characteristic strengths of P50 are found to be greater than the 'wet' mean and characteristic strengths of Occlusin and Silux. The 'wet' mean and characteristic strengths of Occlusin are the lowest. However at 0.01 percent failure probability, the predicted stress by the Weibull statistics for all these materials are approximately the same. The predicted stress at other levels of failure probabilities are varied. In addition the predicted stress by the Normal statistics at all levels of failure probabilities are also varied. Hence Weibull statistics may be suitable to give a reliable prediction at a lower value of failure probability and therefore it is proposed that the failure probability of 0.01 percent may be taken as an arbitrary probability of failure. It is usually not feasible to test 10^4 full-scale prototypes to establish this stress level experimentally. However it has been stated in previous chapters that Weibull statistics is capable of predicting failure outside the stress range in which the material has been tested. This was found when 30 or more specimens were used in the test, as the ~~the~~ correlation coefficient of the test is very high (McCabe et.al: 1990, McCabe and Carrick:1986, McCabe and Walls:1986, Kamiya and Kamigaito:1984, Trustrum and Jayatilaka:1979). Furthermore a reliable prediction may be possible when the crack size distribution is related to the material microstructure (Bever:1986).

Table 8.3.1.1(b) shows the results for each batch of the 'wet' and 'dry' compressive test of Occlusin. The mean strength and deviation coefficient (%) for each batch were calculated. The Weibull modulus and characteristic strength for each batch were predicted by substituting the mean strength and deviation coefficient (%) in equations 7.1 and 7.2 (chapter seven). 'wet' mean and 'wet' characteristic strengths of each batch is not far different from the overall mean and characteristic strengths of all the batches analysed together (Table 8.3.1.1(a)). These may be due to the percentage coefficient of deviation for these batches were all under 5 percent. The value of the Weibull modulus predicted was more than 20 for all the batches. However the 'dry' mean and 'dry' characteristic strengths of each batch different from the over mean strength of all the batches have been analysed together (Table 8.3.1.1(a)). These may be due to the percentage of coefficient deviation for these batches (under 8 percent) were higher than the percentage of coefficient deviation for the batches of the 'wet' strength. For the 'dry' strength, it was noted that the difference in the stress predicted at 0.01% probability of failure by Student and Weibull distributions appeared when the percentage of coefficient deviation was more than 5 percent. The stress predicted either by Student or Weibull distribution equation was approximately the same for the 'wet' strength of Occlusin, particularly at 0.01% probability of failure. However the stress predicted by Normal distribution is significantly different from the stress predicted either by Student or Weibull distribution equation. This shows that Student's distribution is more suitable than the Normal distribution to predict the stress for the small sample. The predicted stress at various levels of failure probability are reported as a bar chart. This is shown in Figures 8.3.1.1(b) and 8.3.1.1(c), respectively for the 'wet' and 'dry' strength of Occlusin. If the mean strength or characteristic strength is used as a criterion to verify the strength of the material, less than 50 percent of the batches (three or less batches) of specimens had a mean or characteristic strength greater than the value of the overall mean or overall characteristic strength when all the data have been cumulatively ~~cummulatively~~ analysed together (as shown in Table 8.3.1.1(a)). Apart from that, most of the brittle material fails at a stress lower than the mean strength. If a stress at 0.01 percent failure probability of the Normal statistics is used as a criterion to verify the strength of the material, less than 50 percent of the batches (three or less batches) of specimens had a stress greater than the overall predicted stress at 0.01 percent failure probability when all the data were cummulatively analysed together (Figure 8.3.1.1(a)) as it produced an under-estimated stress when the deviation coefficient of the batch is more than 5 percent. However if a stress at 0.01 percent failure probability of the Weibull statistics is used as a criterion to verify the strength of the material, more than 50 percent of the batches (three or more batches) of specimens had a stress greater than the overall predicted stress at 0.01 percent failure probability when all the data were cummulatively analysed together (Figure 8.3.1.1(a)).

Tables 8.3.1.2(b) and 8.3.1.3(b) show the results of the 'wet' and 'dry' compressive tests of Silux and P50 where each batch was analysed separately. Both 'wet' and 'dry' mean strengths of Silux and P50 calculated from each batch is severely different from the overall mean strength calculated for the data of all the batches cummulatively analysed together for Silux (as shown in Table 8.3.1.2(a)) and P50 (as shown in Table 8.3.1.3(a)). The same effect is also shown by the 'wet' and 'dry' characteristic strengths of Silux and P50. This may be due to the wide variation of the value of Weibull modulus. The values of the Weibull moduli predicted for batches of the 'wet' and 'dry' strength of Silux were varied from 4 to 27. While the values of the Weibull moduli predicted for batches of the 'wet' strength of P50 varied from 10 to 32 and the values of the Weibull moduli predicted for batches of the 'dry' strength of P50 varied from 5 to 31. The wide variation of the deviation coefficients(%) were also encountered as there is a relation between the Weibull modulus and the deviation coefficients(%). This has been discussed in Chapter Seven. It was noted that the differences in the stress predicted by Student and Weibull distributions appeared when the Weibull modulus was less than 20 or for the deviation coefficient was more than 5 percent. The stress predicted by the Student and Weibull distribution equations were approximately the same for those batches that had the deviation coefficient(%) less than 5 percent (or Weibull modulus more than 20), particularly at 0.01% probability of failure. If the mean strength or characteristic strength is used as a criterion to verify the strength of the material, it was only less than 50 percent of the batches (three or less batches) of specimens that had a mean strength or characteristic strength greater than the value of the overall mean strength or overall characteristic strength when all the data were cummulatively analysed together. Apart from that, most of the brittle material fails at a stress lower than the mean strength. If a stress at 0.01 percent failure of probability of the Normal statistics is used as a criterion to verify the strength of the material, less than 50 percent of the batches (i.e less than three batches) had a stress greater the value of the overall stress predicted at 0.01 percent failure of probability when all the data were cummulatively analysed together as it produced an under-estimated stress when the deviation coefficient of the batch is more than 5 percent. However if a stress at 0.01 percent failure of probability of the Weibull statistics is used as a criterion to verify the strength of the material, more than 50 percent of the batches (i.e more than three batches) had a stress greater the value of the overall stress predicted at 0.01 percent failure probability when all the data were cummulatively analysed together. The predicted stress at various levels of failure probability for the 'wet' and 'dry' strengths of Silux and P50 are shown in Figures 8.3.1.2(b), 8.3.1.2(c), 8.3.1.3(b) and 8.3.1.3(c).

According to the results of the compressive test of light activated composite resin, the mean strength for each batch (of 5 specimens) of the coefficient deviation greater than 5 percent were found to vary substantially from the mean of the group of specimens (i.e 30 Specimens). The difference between the stress predicted by Student and Weibull distributions for the batch for a deviation coefficient less than 5 percent (or Weibull modulus approximately greater than 20) was insignificantly smaller at 0.01% failure probability level when compared with the other probability level. For the batches with a deviation coefficient less than 15 percent (or Weibull modulus approximately greater than 7), the difference between the stress predicted by both distributions at a lower failure probability (0.01%, 0.1 and 1 failure probability level) was acceptable. The difference between the stress predicted by Student and Weibull distributions at a lower failure probability level for those batches of deviation coefficient greater than 15 percent was significantly large. This shows the fact that the Normal distribution is not suitable for estimating the stress especially at a lower probability level.

It has been discussed in Chapter Two that Weibull analysis is not suitable if the number of specimens to be tested is less than 30. However the value of Weibull modulus and characteristic strength of a smaller sample may be estimated from the relationships found in Chapter Seven. This leads to a reliable stress prediction at a lower probability of failure predicted by the Weibull statistics as Normal statistics was found not suitable for assessing the strength at lower failure probability levels. This has been shown in the above paragraph. Therefore the relationships as described in Chapter Seven have proved to be reliable and applicable.

Weibull statistics is found to be a more adaptable method for assessing the strength of the brittle materials. The conclusion of the discussion above was, an arbitrary stress for the failure probability at 0.01 percent should be agreed upon. This character would be a strength parameter in any adjudication made whether any batch of materials would pass or fail the specifications laid upon the material. Therefore the predicted stress at the arbitrary failure probability of 0.01 percent should be greater than the arbitrary stress for compressive strength of light activated composite resins at 0.01 percent failure probability. This stress may be reasonably chosen from the standard biting force or the other design stresses laid down by the manufacturer. Weibull modulus and characteristic strength should also be determined inorder to describe the behaviour of the material. With respect to the results of the compressive tests of light activated composite resins, their compressive strength parameters may be approximately summarised in the Table 8.3. These values were taken from the Tables 8.3.2.1(a), 8.3.2.2(a) and 8.3.2.3(a).

Table 8.3 - The compressive strength parameters for the selected light activated composite resin.

Type of Composite Resin	Weibull Modulus	Characteristic Strength	0.01% Failure Probability
Occlusin (Wet)	25	230 Mpa	160 Mpa
Silux (Wet)	15	310 Mpa	165 Mpa
P50 (wet)	12	350 Mpa	165 Mpa
Occlusin (Dry)	18	220 Mpa	135 Mpa
Silux (Dry)	9	307 Mpa	110 Mpa
P50 (Dry)	12	350 Mpa	160 Mpa

* P.T.O.

*

From Table 8.3 above the characteristic strength of Occlusin is found lower the ~~the~~ characteristic strength of the other composite resin. It is also shown in Table 2.3 and Table 8.3.1.1(a) that the mean compressive strength of Occlusin is lower than the mean strength of P50 (Table 8.3.1.3(a). The strength of occlusin is tought to be similar to the P50 as both of them are hybrid composite. The possible reason for this is that Occlusin is a dense and opaque composite resin than P50. Therefore there the degree of polymerisation in Occlusin specimen is lower than the degree of polymerisation in P50. To overcome this, the Occlusin specimen should not only be cure from both ends but also at the circumference as the depth of cure is

less than depth of cure for P50. The other reason may due to the different type of monomer present in P50. P50 composite resin is based on Bis-GMA without the hydroxy groups.

8.3.2 Compressive Test of Dental Amalgam

Amalcap and Dispersalloy were the two types of dental amalgam that have been used in this work. The difference between them is that Amalcap is a conventional silver-tin amalgam while Dispersalloy is a 'gamma-2' free amalgam. Two groups of specimens of 4 mm diameter by 6 mm length were prepared for each material. One group of specimens was stored in a 'wet' condition and other was stored in a 'dry' condition. A crosshead speed of 0.1 mm per minute was used for the test.

Oneway analysis of variance showed that there was a significant difference between the compressive strength of the specimens stored in 'wet' condition when compared with the compressive strength of the specimens stored in 'dry' condition for both dental amalgams ($p<0.001$). This is shown clearly in Figures 8.3.2.1(a) and 8.3.2.2(a) where the curves for 'dry' and 'wet' specimens are well apart. However, for the Dispersalloy, the curves are converging at a higher level of probability. The stress estimated by the Weibull distribution equation at this level for both groups was equal to 410 MPa. The stress predicted by the Normal distribution equation was less accurate.

The 'wet' specimens of Amalcap were less brittle than the 'dry' specimens. This shown by the higher value of Weibull modulus for the 'wet' specimens of Amalcap (Table 8.3.2.1(a)). This was not the case for Dispersalloy. The 'wet' specimens of Dispersalloy were more brittle than the 'dry' specimens. The value of Weibull modulus for the dry specimens of Dispersalloy was higher than the value of Weibull modulus for the 'wet' Dispersalloy specimens. These show that the storage conditions have affected the brittleness of the amalgam. Amalcap becomes more brittle when exposed to a 'dry' environment and Dispersalloy becomes more brittle when exposed to 'wet' environment. Thus the selection of materials with respect to environmental needs is necessary so that the strength of the materials can be optimised. However in this case the performance at a lower failure probability of Amalcap is better than Dispersalloy when subjected to both storage conditions. This can be seen in Table 8.3.2.1(a), the predicted stress at the lower failure probability levels (0.01% and 1%) are higher for the compressive strength of Amalcap for both 'wet' and 'dry' specimens when compared with the predicted stress at the lower failure probability of the 'wet' and 'dry' specimens of Dispersalloy (Table 8.3.2.2(a)). One of the reasons may be because the compressive strength of Amalcap is higher than the compressive strength of Dispersalloy. The other may be due to the scatter of the results. The scatter of the results is shown by the value of Weibull modulus. The value of Weibull modulus may also indicates the degree of brittleness. The results of the 'wet' and 'dry' specimens of Dispersalloy are more scattered than the results for Amalcap. This may be because of the mode of failure. A catastrophic failure was experienced with the non 'gamma-2' (Vaindyathan and Schulman:1979). It resulted from crack propagated along the silver-mercury and silver-copper eutectic interface. The values of Weibull moduli for the 'wet' and 'dry' specimens of Amalcap are significantly greater than the values of Weibull moduli for the 'wet' and 'dry' specimens of Dispersalloy. This may be due to the plastic deformation experienced at failure when the specimens were tested at a low strain rate under compression (Vaindyathan and Schulman:1979). The ductility of the Tin-Mercury phase in a Silver-Tin amalgam was reported by Young and Wilsdorf (Young and Wilsdorf:1968).

Tables 8.3.2.1(b) and 8.3.2.2(b) show the results for each group of specimens analysed according to their batches. The 'wet' and 'dry' mean strength calculated for each batch varied substantially. Their coefficient of deviation (%) were also varied. From the mean and coefficient of deviation, the characteristic strength and Weibull modulus for each batch was estimated.

The stress predicted by the Normal distribution at a low levels of failure probability (0.01%, 0.1% and 1%) were greatly different from the stress predicted by the Weibull distribution equation. As had been discussed previously in section 8.3.1, the Normal prediction gave an under-estimated stress when the percentage of coefficient deviation of the sample was more than 5 (or Weibull modulus less than 20). At a high level failure probability (99.99%), the Normal prediction gave an over-estimated stress when the percentage of coefficient deviation of the sample was more than 15. The stress estimated by the Normal distribution and the Weibull distribution equation was very large, and the stress estimated by the Normal distribution was over estimated when compared to the stress predicted by the Weibull distribution equation. This shows that the Normal distribution is not suitable for estimating the stress especially at a lower probability level. That is why the mean strength is accepted if the percentage of deviation coefficient is less than 15 percent. Otherwise the mean value of the sample has been discarded (British ~~Bristich~~ Standard BS:2938:1985).

The mean strength and characteristic strength are not suitable criterion for accessing the strength of brittle materials. This has been discussed ~~disscussed~~ in section 8.3.1. If the mean strength or characteristic strength is used, it was only less than 50 percent of the batches (three or less batches) of specimens had a mean strength or characteristic strength greater than the value of the overall mean strength or overall characteristic strength when all the data have been cummulatively analysed together. The stress at 0.01 percent failure probability estimated by Normal statistics is also found to be an unsuitable criterion for accessing the strength as it produced an under-estimated stress when the deviation coefficient of the batch is more than 5 percent. If a stress at 0.01 percent failure of probability of the Normal statistics is used, less than 50 percent of the batches (i.e less than three batches) had a stress greater the value of the overall stress predicted at 0.01 percent failure of probability when all the data were cummulatively analysed together. However the stress at 0.01 percent failure probability estimated by Weibull statistics is found to be a suitable criterion for assessing the compressive strength of light activated composite resins. It gave more than 50 percent of the batches (i.e more than three batches) had a stress greater the value of the overall stress predicted at 0.01 percent failure of probability when all the data were cummulatively analysed together. Therefore the relationships as described in Chapter Seven has proved to be reliable and applicable. This finding is also true for the compressive strength of dental amalgam. The predicted stress at various levels of failure probability for the 'wet' and 'dry' strengths of Amalcap and Dispersalloy were reported in the form of bar chart and are shown in Figures 8.3.2.1(b), 8.3.2.1(c),8.3.2.2(b) and 8.3.2.2(c).

Weibull statistics is found to be a more adaptable method for ~~acessing~~ accessing the strength of the brittle materials. The conclusion of the discussion above was, an arbitrary stress for the failure probability at 0.01 percent should be agreed upon. This character would be a strength parameter in any adjudication made whether any batch of materials would pass or fail the specifications laid upon the material. With respect to the results of the compressive tests of dental amalgam, the compressive strength parameters for the Dental Amalgam can be reasonable outlined. The compressive strength parameters for the silver-tin amalgam and non 'gamma-2' amalgam which was subjected to different degree of moisture contamination may be approximately summarised in the Table 8.4. These values were taken from the Tables 8.3.2.1(a) and 8.3.2.2(a).

Table 8.4 - The compressive strength parameters of the selected dental amalgam.

Type of Dental Amalgam	Weibull Modulus	Characteristic Strength	0.01% Failure Probability
Amalcap (Wet)	23	410 Mpa	275 Mpa
Dispersalloy (Wet)	10	350 Mpa	140 Mpa
Amalcap (Dry)	19	380 Mpa	235 Mpa
Dispersalloy (Dry)	15	370 Mpa	200 Mpa

P.T.O.*

*

The compressive strength of amalcap obtained from this test is about the same as produced by McCabe (McCabe et al:1990). The value of compressive strength of amalcap is shown in Table 2.4. However McCabe used different ageing period. The compressive strength for Dispersalloy is not found recorded in the literature. However from this test it showed that the compressive strength of Dispersalloy is lower than the compressive strength of Amalcap.

P.T.O.

8.3.3 Compressive Test of Dental Cements.

Ketac-Fil and Ketac-Silver were two types of dental cement used in this study. Only one group of specimens was prepared for each material. These specimens were stored under 'wet' condition. Table 8.3.3.1(a) shows that Ketac-Fil is more brittle than Ketac-Silver. The value of the Weibull modulus for Ketac-Silver is higher than that for Ketac-Fil. Figure 8.3.3.1(a) show that the performance of the Ketac-fil at a very low probability level is better than the performance of the Ketac-silver. However the overall performance of the Ketac-Silver specimens is better than Ketac-fil at other levels of failure probability. These stresses have been predicted correctly by both Weibull and Normal analysis, but the stresses estimated by the Normal analysis are higher than the stresses estimated by Weibull analysis.

The results for each group of material, analysed by its batches, are shown in Table 8.3.3.1(b). The mean strength for each batch was significantly different from the others. The mean strength for the batches of the Ketac-Fil specimens ranged from 169 MPa to 215 MPa. The mean strengths for the batches of Ketac-Silver specimens ranged from 169 MPa to 197 MPa. The percentage of deviation coefficient for the batches of Ketac-Fil specimens was greater than 10 (or Weibull modulus less than 10). However the percentage of deviation coefficient for the batches of Ketac-Silver specimens was less than 10 (or Weibull modulus greater than 10). This shows that the Ketac-Silver specimens were less brittle than Ketac-Fil specimens. As previously discussed that the degree of the brittleness can be related to the value of Weibull modulus i.e the lesser the value of Weibull modulus the higher the degree of brittleness. The degree of brittleness can be also related to the scatter of test data and it is measured by the deviation coefficient. Thus the brittleness may be a measured of the scatter of test data.

The predicted stress by Weibull and student distributions at a lower levels of failure probability (0.01%,0.1% and 1%) were approximately the same for the percentage of deviation of 5 percent or less. This is shown in Figure 8.3.3.1(b) and (c) that the same height of the bar chart. The predicted stress at other probability level, the difference between the stress estimated by Student distribution and Weibull distribution equation was very large. This was true even at a lower percentage of deviation coefficient. Furthermore the stress estimated by Normal distribution was over estimated when compared to the stress predicted by Weibull distribution equation.

The mean strength ,characteristic strength and the stress at 0.01 percent failure probability estimated by Normal statistics are not suitable criteria for assessing the strength of the brittle materials for the same reason that has been discussed in section 8.3..1. The stress at 0.01 percent failure probability estimated by Weibull statistics is found to be suitable criterion for assessing the compressive strength of dental cements. Therefore the relationships as described in Chapter Seven have proved to be reliable and applicable. This finding is in agreement with the ~~the~~ compressive strength of light activated composite resin and dental amalgam.

Weibull statistics therefore is found to be a more adaptable method for acessing the strength of the brittle materials. The conclusion of the discussion above was, an arbitrary stress for the failure probability at 0.01 percent is a suitable strength parameter. It may be used in any adjudication made whether any batch of materials would pass or fail the test specifications. Hence, the summary of the compressive strength parameters of the selected dental cement is shown in the Table 8.5. These values were taken approximately from Table 8.3.3.1(a).

Table 8.5 - The compressive strength parameters of the selected dental cement.

Type of Dental Cements	Weibull Modulus	Characteristic Strength	0.01% Failure Probability
Ketac-Fil	7	220 Mpa	60 Mpa
Ketac-Silver	15	190 Mpa	100 Mpa

Table 8.5 shows the compressive strength of Ketac silver is lower than the compressive strength of Ketac fil. This is in agreement with the finding of the other workers (McCabe et al:1990, Wong T.C.C:1985, Walls et al:1987, Williams J.A and Billington R.W:1989 and Mount G.J:1989)

8.3.4 Diametral Tensile Test of Light Activated Composite Resin

Tables 8.3.4.1(a), 8.3.4.1(b) and Figures 8.3.4.1(a), 8.3.4.1(b) and 8.3.4.1(c) are the results for the diametral tensile test of Occlusin. Tables 8.3.4.2(a), 8.3.4.2(b) and Figures 8.3.4.2(a), 8.3.4.2(b) and 8.3.4.2(c) are the results for the diametral tensile test of Silux. The results for the diametral tensile test of P50 are shown in Tables 8.3.4.3(a), 8.3.4.3(b) and Figures 8.3.4.3(a), 8.3.4.3(b) and 8.3.4.3(c)

Oneway analysis of variance showed that there was a significant difference between the diametral tensile strength of the specimens stored in the 'wet' condition when compared with the diametral tensile strength of the specimens stored in the 'dry' condition [$P<0.05$] for all types of composite resins. This effect can be seen clearly in Figures 8.3.4.1(a), 8.3.4.2(a) and 8.3.4.3(a) . The curve for 'wet' specimens was separated from the curve for the 'dry' specimens.

The correlation coefficient of the 'wet' specimens was better than the correlation coefficient of the 'dry' specimens. This means that the Weibull distribution is a better 'fit' to the test of the 'wet' specimens.

The value of Weibull modulus of the 'wet' specimens was also higher than the Weibull modulus of the 'dry' specimens. This means that 'dry' specimens are more brittle than 'wet' specimens. However the diametral tensile strength of the 'wet' specimens was higher than the diametral tensile of the 'dry' specimens. This can be seen from the Figures 8.3.4.1(a), 8.3.4.2(a) and 8.3.4.3(a). The curve for the 'wet' specimens and the curve for the 'dry' specimen of P50 give the largest gap, followed by Silux and finally by Occlusin. This shows that storage conditions affect the diametral tensile strength of light-activated composite resins and the effect varies from one material to another. In this case, the diametral tensile strength of Occlusin is more stable to environmental change than the other materials.

Tables 8.3.4.1(b), 8.3.4.2(b) and 8.3.4.3(b) show the results for the data when each batch from each group is analysed separately. The mean strength of each batch closely agreed with the overall mean strength when all the data in each batch have been cummulatively analysed. The predicted characteristic strength also closely agreed with the overall characteristic strength when all the data in each batch were cummulatively analysed. The difference between the stress predicted by Weibull and Student distribution equations at 0.01% failure probability is significantly different when the percentage of coefficient deviation is more than 5 percent. The mean strength and characteristic strength are not suitable criteria for assessing the strength of the brittle materials. This has been disscussed in section 8.3.1. The stress at 0.01 percent failure probability estimated by Normal statistics is also found to be an unsuitable criterion for assessing the strength. However the stress at 0.01 percent failure probability estimated by Weibull statistics is found to be a suitable criterion for assessing the strength. This finding is also in agreement with the diametral tensile strength of light activated composite resins. Therefore Weibull statistics is found to be a more adaptable method for acessing the strength of the brittle materials. This shows that the value of Weibull modulus and characteristic strength predicted by the equations 7.1 and 7.2 (as shown in Chapter Seven) are reliable and applicable.

With respect to the results of the diametral tensile tests of light activated composite resins, their diametral tensile strength parameters may be approximately summarised in the Table 8.6. These values were taken from the Tables 8.3.4.1(a), 8.3.4.2(a) and 8.3.4.3(a).

The results of the diametral tensile strength obtained from this investigation (Tables 8.3.4.1(a), 8.3.4.2(a), 8.3.4.3(a) and 8.6) was in agreement with the results (Table 2.3) of the other workers (McCabe et al:1990, Oysaed H

and Ruyter I.E:1986, Bryant R.W and Mahler D.B:1986, Fraunhofer J.A and Curtis P.Jr:1989 and Chung K.H:1989)

Table 8.6 - The diametral tensile strength parameters of the selected light activated composite resins.

Type of Composite Resin	Weibull Modulus	Characteristic Strength	0.01% Failure Probability
Occlusin (Wet)	21	55 Mpa	35 Mpa
Silux (Wet)	12	37 Mpa	17 Mpa
P50 (wet)	9	60 Mpa	22 Mpa
Occlusin (Dry)	17	55 Mpa	30 Mpa
Silux (Dry)	9	35 Mpa	13 Mpa
P50 (Dry)	7	55 Mpa	15 Mpa

8.3.5 Diametral Tensile Test of Dental Amalgam

Only two types of dental amalgam were tested. These were Amalcap and Dispersalloy. The results of the diametral tensile test of Amalcap are shown in Tables 8.3.5.1(a) and 8.3.5.1(b), and Figures 8.3.5.1(a), 8.3.5.1(b) and 8.3.5.1(c). The results of the diametral tensile test of Dispersalloy are shown in Tables 8.3.5.2(a) and 8.3.5.2(b), and Figures 8.3.5.2(a), 8.3.5.2(b) and 8.3.5.2(c).

Oneway analysis of variance showed that there was no significant difference between the diametral tensile strength of the specimens stored in 'wet' conditions when compared with the diametral tensile strength of the specimens stored in 'dry' conditions [P>0.05]. This is shown clearly in Figures 8.3.5.1(a) and 8.3.5.2(a), by the fact that the curve for both 'wet' and 'dry' specimens are close to each other. Thus it can be said that the diametral tensile strength of Amalcap and Dispersalloy are stable to environmental change. The mean and the characteristic diametral tensile strength of Amalcap and Dispersalloy were approximately the same for both 'wet' and 'dry' specimens. The mean and characteristic strength for the 'dry' specimens are doubtful because their correlation coefficients are low. For the same reason, the value of Weibull modulus of the 'dry' specimens is also doubtful. It is observed from Tables 8.3.5.1(a) and 8.3.5.2(a) that the correlation coefficient for the 'dry' specimens was less than the correlation coefficient for the 'wet' specimens. This shows that the Weibull distribution 'fitted' better to the test of 'wet' specimens.

The Weibull modulus of the 'wet' specimens of Amalcap is higher than the Weibull modulus of the 'wet' specimens of Dispersalloy. This means that the 'wet' specimens of Dispersalloy are more brittle than the 'wet' specimens of Amalcap. 'wet' mean and 'wet' characteristic diametral tensile strength of Amalcap and Dispersalloy were the same but the stress at a low probability of failure for Amalcap was greater than that calculated for Dispersalloy. Therefore the performance of Amalcap was better than Dispersalloy.

Tables 8.3.5.1(b) and 8.3.5.2 (b) show the percentage of deviation coefficients calculated for all the batches are more than 5 percent. This makes the predicted stress by the Weibull and the Student distribution equations at lower levels of failure probability differ substantially. The mean strength and characteristic strength are not suitable criteria for assessing the strength of the brittle materials. This has been disscussed in section 8.3.1. The stress at 0.01 percent failure probability estimated by Student distribution is also found to be an unsuitable criterion for assessing the strength as it produced an under-estimated stress when the deviation coefficient of the batch is more than 5 percent. However the stress at 0.01 percent failure probability estimated by Weibill statistics is found to be suitable criterion for assessing the compressive strength. This finding is also true for the diametral tensile strength of dental amalgam.

With respect to the results of the diametral tensile tests of dental amalgam, the compressive strength parameters for the selected Dental Amalgam can be reasonable outlined. The diametral tensile strength parameters for the silver-tin amalgam and non 'gamma-2' amalgam which was subjected to a different degree of moisture contamination may be approximately summarised in the Table 8.7. These values were taken from the Tables 8.3.5.1(a) and 8.3.5.2(a).

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The diametral strength of Amalcap and Dispersalloy are found approximately the same. The results for the diametral tensile strength of amalgam obtained in this test is also in agreement with the result obtained by Fraunhofer et al:1989). However the result for the diametral tensile strength of Dispersalloy by other workers is not found recorded in the literature.

Table 8.7 - The diametral tensile strength parameters for the selected Dental Amalgam.

Type of Dental Amalgam	Weibull Modulus	Characteristic Strength	0.01% Failure Probability
Amalcap (Wet)	6	40 Mpa	8 Mpa
Dispersalloy (Wet)	5	40 Mpa	5 Mpa
Amalcap (Dry)	7	35 Mpa	10 Mpa
Dispersalloy (Dry)	6	40 Mpa	10 Mpa

8.3.6 Diametral Tensile Test of Dental Cements

Ketac-Fil and Ketac-Silver were the two types of dental cement used in this study. Only one group of specimens was prepared for each material. These specimens were stored in 'wet' conditions. Figure 8.3.6.1(a) shows that the curves for the Ketac-Fil and Ketac-Silver specimens are very similar. This shows that both materials are of the same brittleness when the specimens are tested for diametral tensile strength. This also shows that the performance of the diametral tensile strength for both materials are the same. However this is not the case for the compressive strength of Ketac-fil and Ketac-Silver (see section 8.3.3). While Table 8.3.6.1(a) shows that the mean strength and characteristic strength for Ketac-Fil and Ketac-Silver are approximately the same. The percentage of deviation coefficient of the Ketac-Fil specimens is higher than that of the Ketac-Silver specimens. That is why the Weibull modulus of the Ketac-Silver specimens is higher than that of the Ketac-Fil specimens. This may be due to the fact that the data of the Ketac-Fil specimens does not fit the Weibull or Normal distribution equations very well as the correlation coefficient for the Ketac-Fil specimens is less than Ketac-Silver specimens.

The results for each group of material analysed according to batch are shown in Table 8.3.6.1(b). The mean strength for each batch was significantly different from the others. The predicted stress by Weibull and Normal analysis at lower failure probability were different because the percentage of deviation of the batch was more than 5 percent. Furthermore the stress estimated by the Normal distribution was under-estimated when compared to the stress predicted by the Weibull distribution equation. The mean strength and characteristic strength are not suitable criteria for assessing the strength of the brittle materials for the same reason that has been disscussed in section 8.3.1. The stress at 0.01 percent failure probability estimated by Normal statistics is also found to be an unsuitable criterion for assessing the strength as it produced an under-estimated stress when the deviation coefficient of the batch is more than 5 percent. However the stress at 0.01 percent failure probability estimated by Weibull statistics is also found to be a suitable criterion for assessing the diametral tensile strength of dental cements.

With respect to the results of the diametral tensile tests of dental cements, the diametral tensile strength parameters for the selected dental cements under test is shown in the Table 8.8. These values were taken approximately from Table 8.3.6.1(a).

Table 8.8 - The diametral tensile strength parameters for the selected dental cements.

Type of Dental Cements	Weibull Modulus	Characteristic Strength	0.01% Failure Probability
Ketac-Fil	3.5	13 Mpa	1 Mpa
Ketac-Silver	4.5	13 Mpa	2 Mpa

8.3.7 Flexural Test of Light Activated Composite Resins

Oneway analysis of variance showed that there was a very highly significant difference between the flexural strength of the 'wet' specimens when compared with the flexural strength of the 'dry' specimens for both Silux and P50. Figures 8.3.7.1(a) and 8.3.7.2(a) show that the flexural strength of the 'wet' specimens is greater than the flexural strength of the 'dry' specimens. Tables 8.3.7.1(a) and 8.3.7.2(a) show that the 'wet' mean flexural strength of Silux and P50 are greater than their 'dry' mean flexural

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Table 8.8 shows the diametral tensile strength for Ketac fil and Ketac silver are the same. The results for the diametral tensile strength of dental cement obtained in this test is not agreement with the the result (Table 2.5) produced by Mount (Mount G.J:1989). This may be because of different ageing period.

strength. The 'wet' mean flexural strength of P50 is greater than the 'wet' flexural strength of Silux. The percentage of deviation coefficient for the 'wet' and 'dry' flexural strengths of Silux is approximately the same. As a result, the Weibull modulus for both groups are the same. Even though the Weibull modulus is the same, the mean flexural strength of the 'wet' specimens is greater than the mean flexural strength of the 'dry' specimens. This means that the mean flexural strength becomes less when the specimens are left in a 'dry' condition. However the percentage of deviation coefficient for the 'dry' flexural strength of P50 is almost double the percentage of deviation coefficient for the 'wet' flexural strength of P50. The 'dry' P50 specimens are more brittle than the 'wet' P50 specimens. The mean flexural strength of P50 becomes less when the specimens are left in a 'dry' condition. According to the stress at a lower probability of failure, the performance of the 'wet' specimens was better for P50 but for the 'dry' specimens, Silux performed better than P50.

Tables 8.3.7.1(b) and 8.3.7.2(b) show the Weibull parameters have been predicted by using the mean and the coefficient of deviation (%) from data collected from 5 specimens. Using these values, stresses at several probabilities of failure were estimated. The difference between the stress predicted by Student and Weibull distribution equations at 0.01% probability of failure was reasonably small when the percentage of deviation coefficient was less than 5 percent. The use of the Student distribution to predict the stress at this level for the percentage of deviation coefficient more than 5 percent would lead to an under-estimation of the failure stress when the deviation coefficient of the batch is more than 5 percent. The mean strength and characteristic strength are not suitable criteria for assessing the strength of the brittle materials for the same reason that has been disscussed in section 8.3.1. The stress at 0.01 percent failure probability estimated by Normal statistics is also found to be an unsuitable criterion for assessing the strength as it produced an under-estimated stress when the deviation coefficient of the batch is more than 5 percent. However the stress at 0.01 percent failure probability estimated by Weibill statistics is also found to be a suitable criterion for assessing the flexural strength of light activated composite resins.

With respect to the results of the flexural tests of light activated composite resins, the flexural strength parameter for the selected light activated composite resins are shown in the Table 8.9. These values were taken approximately from Tables 8.3.7.1(a) and 8.3.7.2(a).

> It has been shown than the flexural strength of Opalux is higher than the flexural strength of Occlusin and Silux (Table 2.3). The flexural strength for P50 is not recorded in the literature. The flexural strength of Silux however is found higher when compared to the flexural strength produced by Bryant and Mahler (Bryant R.W and Mahler D.B:1986) that has been shown in Table 2.3.

Table 8.9 - The flexural strength parameter for the selected light activated composite resins.

Type of Composite Resin	Weibull Modulus	Characteristic Strength	0.01% Failure Probability
Silux (wet)	11	120 Mpa	52 Mpa
P50 (wet)	8	225 Mpa	68 Mpa
Silux (dry)	10	100 Mpa	40 Mpa
P50 (dry)	5	190 Mpa	27 Mpa

8.3.8 Flexural Test of Dental Amalgam

Oneway analysis of variance showed that there was a highly significant difference between the flexural strength for the 'wet' specimens when compared with the flexural strength for the 'dry' specimens. This effect can be seen clearly in Figures 8.3.8.1(a) and 8.3.8.2(a) where the Weibull curves for the 'wet' and 'dry' specimens were separated from each other and the strengths at given probabilities for the 'wet' specimens were lower than of those the 'dry' specimens. It was noted form Tables 8.3.8.1(a) and 8.3.8.2(a) that the 'dry' mean flexural strength of Amalcap and Dispersalloy were greater than their 'wet' mean flexural strengths. This showed that the storage conditions affect the flexural strength of Amalcap and Dispersalloy. The percentage of deviation coefficient of the 'wet' Dispersalloy specimens was greater than the deviation coefficient of the 'wet' Amalcap specimens. For the Weibull distribution equation, this means that the Weibull modulus of Amalcap is higher than the Weibull modulus of Dispersalloy. This shows that the 'wet' Dispersalloy specimens are more brittle than the 'wet' Amalcap specimens. This may be because of the mode of failure. A catastrophic failure was experienced with the non 'gamma-2' amalgams (Vaindyathan and Schulman:1979). It resulted from crack propagated along the silver-mercury and silver-copper eutectic interface. The values of Weibull moduli for the 'wet' specimens of Amalcap are significantly greater than the values of Weibull moduli for the 'wet' specimens of Dispersalloy. This may be due to the plastic deformation experienced at failure when the specimens were tested at a low strain rate under compression (Vaindyathan and Schulman:1979). The ductility of the Tin-Mercury phase in a Silver-Tin amalgam was reported by Young and Wilsdorf (Young and Wilsdorf:1968). However the deviation coefficients and Weibull modulus of 'dry' specimens of Amalcap and Dispersalloy are approximately the same. This shows that the ductility of the Tin-Mercury phase increases as it is Severely ~~severvely~~ exposed to moisture contamination.

Tables 8.3.8.1(b) and 8.3.8.2(b) show that the coefficient of deviation(%) calculated for each batch varies. However Figures 8.3.8.1(b), 8.3.8.1(c), 8.3.8.2(b) and 8.3.8.2(c) show a bar chart showing the stress at 0.01% probability of failure predicted by the Student distribution for the batch of a coefficient deviation of less than 5 percent is approximately the same ~~hight~~ height when compared with the stress predicted by the Weibull distribution equation at the same probability level. The mean strength and characteristic strength are not suitable criteria for assessing the strength of the brittle materials for the same reason that has been disscussed in section 8.3.1. The stress at 0.01 percent failure probability estimated by Normal statistics is also found to be an unsuitable criterion for assessing the strength as it produced an under-estimated stress when the deviation coefficient of the batch is more than 5 percent. The stress at 0.01 percent failure probability estimated by Weibill statistics is found to be a suitable criterion for assessing the flexural strength of dental amalgam.

With respect to the results of the flexural tests of dental amalgam, the flexural strength parameters of the selected dental amalgam is summarised in the Table 8.10. These values were taken approximately from Tables 8.3.8.1(a) and 8.3.8.2(a).

Table 8.10 shows the flexural strength of Amalcap is less than the flexural strength of Dispersalloy. The current value of the flexural strength of amalcap is not found in the literature. The flexural strength of Dispersalloy obtained from literature is equal to 103 Mpa. This is produced by Bryant and Mahler (Bryant R.W and Mahler D.B:1986) that has been shown in Table 2.4. However this value is not in agreement with the results from Table 8.10.

Table 8.10 - The flexural strength parameters of the selected dental amalgam.

Type of Dental Amalgam	Weibull Modulus	Characteristic Strength	0.01% Failure Probability
Amalcap (wet)	12	120 Mpa	55 Mpa
Dispersalloy (wet)	6	130 Mpa	25 Mpa
Amalcap (dry)	12	130 Mpa	60 Mpa
Dispersalloy (dry)	13	145 Mpa	73 Mpa

8.3.9 Flexural Test of Dental Cements

Figure 8.3.9.1(a) shows that the Weibull curves for the Ketac-fil and Ketac-silver specimens are approximately parallel to each other. This indicates that both materials have the same value of Weibull modulus but are of different flexural strength. It also shows that the mean and characteristic flexural strengths for the Ketac-Silver are higher than those for the Ketac-Fil specimens. It is clear that the performance of the Ketac-Silver is better than the Ketac-Fil.

Table 8.3.9.1(b) shows the results for each batch that was analysed separately. The mean strength and the percentage of deviation coefficient were calculated for each batch. With these values, the Weibull parameters and stress at failure probability were estimated. The predicted stress by Weibull and Student distribution at a lower levels of failure probability (0.01%, 0.1% and 1%) were approximately the same when the deviation coefficient of the batch was 5 percent or less. At other probability levels, the difference between the stress estimated by the Normal distribution and the Weibull distribution equation was very large.

The stress at 0.01 percent failure probability estimated by Weibill statistics is also found to be a suitable criterion for assessing the flexural strength of dental cements. With respect to the results of the flexural tests of dental amalgam, the flexural strength parameters for the selected dental cements are shown in the Table 8.11. These values were taken approximately from Table 8.3.9.1(a).

Table 8.11 - The flexural strength parameters for the selected dental cements.

Type of Dental Cements	Weibull Modulus	Characteristic Strength	0.01% Failure Probability
Ketac-Fil	6	35 Mpa	8 Mpa
Ketac-Silver	7	42 Mpa	12 Mpa

8.4 Summary and Conclusions

The strength parameters of the selected restorative brittle materials for various mechanical tests have been summarised under each section. The mean strength and the percentage of

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It has been shown in Table 2.5 that the flexural strength of Ketac silver was found the same by different worker. However there is significant difference between the value for the flexural strength of Ketac fil. Walls (Walls et al:1987) produced a higher value of flexural strength for Ketac fil than Ketac silver. The results for the flexural strength of Ketac fil and Ketac silver shown in Table 8.11 is different from Walls (Walls et al:1987). However this results is in agreement with the results from Pearson (Pearson et al:1988).

deviation coefficient of a group of 5 specimens can be used to estimate the Weibull modulus and characteristic strength. This was carried out by substituting the values of mean strength and deviation coefficient(%) in appropriate equations suggested in Chapter Seven. By using the predicted Weibull modulus and the characteristic strength, more than 50 percent of the stress predicted at a lower levels of failure probability were higher than the overall stress at the same level of failure probability when the data was accumulatively analysed together. The stress at a lower levels of failure probability predicted by Student distribution from the mean strength and deviation coefficient(%) of a batch (5 sample size) was under-estimated. The stress predicted at a failure probability greater than 1 percent was over-estimated. This shows that Weibull statistics is more reliable in predicting the stress at lower failure probability levels. It also proved to be reliable for assessing the strength of the material. However the stresses predicted by both Weibull and Normal analysis at lower levels of failure probability are the same when the percentage of deviation coefficient of the batch of a small sample is less than 5 percent. Nevertheless the deviation coefficient of the test for the brittle materials seldom fall below 5 percent.

CHAPTER NINE

CONCLUSIONS

9.1 Crosshead Speed Used For Testing.

An analysis of variance has shown that the most suitable crosshead speed varied with specimen size. It has been shown that a crosshead speed of 0.1 mm per minute gives a sensible result for the compressive test. A crosshead speed of 0.5 mm per minute has given the most sensible results for the diametral tensile test and the flexural test. These results have shown that the deviation of the individual stress from mean stress for each mechanical test was approximately the same when tested with the correct crosshead speed.

9.2 Specimen Size

An analysis of variance has showed that specimen size affects the mechanical strength of the material. The specimens of diameter/depth ratios equal or greater than 2:3 give sensible result for the compressive strength. However specimens of 4 mm diameter by 6 mm depth were found to give the most sensible results when a crosshead speed of 0.1 mm per minute was used.

A specimen of diameter/depth ratio 4:3 was found to give sensible results for the diametral tensile strength test. However the specimens of 4 mm diameter by 3 mm depth showed the most sensible results. In addition, the test was carried out at a crosshead speed of 0.5 mm per minute.

The flexural strength of the specimens of span/depth ratios 5:1 to 15:1 were mentioned in Chapter Two as not being significantly different from each other. However it was found that the flexural strength for the specimens of span/depth ratios below 5:1 were also not significantly different from each other. This was obtained from the test carried out at a crosshead speed of 0.1 mm per minute with a span of 10 mm. The flexural strength of the specimens of span/depth ratios 5:1 to 15:1 were not significantly different from each other when the test was carried out at a crosshead speed equal to or greater than 0.5 mm per minute.

9.3 Brittleness of Brittle Materials.

The Weibull modulus describes the brittleness of the materials. A high value of Weibull modulus indicates a close scatter of a data. A wide scatter of data is shown by a low value of Weibull modulus. The scatter of the data can also be obtained by calculating the deviation coefficient of the specimens. A high value of deviation coefficient shows a wide scatter of data and vice-versa.

9.4 Performance of Brittle Materials

The performance of brittle materials can be determined by calculating the stress at a low probability of failure level. To serve this purpose an abritrary probability level must be chosen. The arbitrary ~~abritrary~~ probability level may be chosen according to the application of the materials. A probability of failure of 0.01 percent is found reliable for the an abritrary probability level.

The stress predicted by Normal analysis at the abritrary probability level of 0.01 percent was under-estimated when compared with the stress predicted by Weibull analysis. The predicted stresses at other levels of failure probability were over-estimated. That is why many specimens fracture below the predicted stress. Thus the performance of the material is over estimated by Normal analysis.

9.5 Stress and Probability of Failure

The stress predicted by Normal analysis at failure probability greater than 1 percent is higher when compared to the stress predicted by Weibull analysis, for the test of a group of 30 specimens. The stress predicted by Normal analysis at 0.01 percent probability of failure is less than the stress predicted by Weibull analysis when a batch of 5 specimens is analysed. This is true for a deviation coefficient more than 5 percent. The stress predicted by

Normal and Weibull analysis at a failure probability less than 1 percent is approximately the same when the deviation coefficient is less than 5 percent. The deviation coefficient of a batch of 5 specimens must be less than 5 percent for the stress at a failure probability less than 1 percent to be correctly predicted by both analysis. However it is almost impossible for the brittle materials to have a deviation coefficient less than 5 percent. Thus Normal analysis may not be suitable for predicting the stress at a failure probability level less than 1 percent.

9.6 Number of specimens required for testing

The test that was carried out with a batch of 5 specimens was not suitable. As has been discussed previously, the brittleness of the materials cannot be judged by using the deviation coefficient of a batch of 5 specimens. The performance of the materials also cannot be judged because the stress at a low probability of failure is severely under estimated by Normal analysis. It may lead to the incorrect judgement of the performance of the materials when the deviation coefficient of a batch of 5 specimens is more than 5 percent. It is rare that the deviation coefficient of 5 specimens will be less than 5 percent.

Another problem with Normal analysis is that the stress predicted is higher when compared to the stress predicted by Weibull analysis for a batch of 30 specimens. For the test using a batch of 5 specimens, the predicted stress at a failure probability level less than 1 percent is severely under estimated especially when the deviation coefficient is more than 5 percent. The predicted stress by Normal analysis at a probability level of more than 1 percent is higher when compared with the predicted stress by Weibull analysis.

9.7 Recommendations for The Application of Weibull Analysis.

A recommendation for the application of Weibull statistics is based on the mean and deviation coefficient of a batch of 5 specimens. The characteristic strength and the Weibull modulus are estimated by using the relationships 7.1 and 7.2. The acceptance level of failure of probability of 0.01 percent is suggested for use for the mechanical testing of the dental restorative materials. The stress at 0.01 percent probability of failure is predicted by using the Weibull distribution equation. An arbitrary pass/fail stress at this probability level must be set for a standard testing procedure. Thus for each material, there must be a pass/fail stress for all types of mechanical testing.

The pass/fail criteria is not an unfamiliar term in standard testing procedures. ISO 1559 for dental amalgam sets a pass/fail requirement for the 24 hours mean compressive strength of 300 MPa and a coefficient deviation of less than

15 percent. ISO DP 9917, the harmonization of tests for dental cements, sets a requirement for the 24 hours compressive strength of at least four specimens must be greater than 130 MPa. For the composite resin filling materials, ISO DIS 4049 states that the material should have a value of flexural strength of 50 MPa or greater.

Based on the results of this investigation, an arbitrary pass/fail stress for the compressive strength for the composite resins and amalgam at 0.01 percent probability of failure is 100 MPa could be chosen. For the compressive strength of dental cements, an arbitrary stress of 50 MPa ~~was~~ could be chosen. The values for the diametral tensile stress predicted at 0.01 percent probability of failure for all the materials are all very small. Due to this reason, an abritrary stress at this probability level may not be suitable for the diametral tensile tests. Therefore diametral tensile tests for the dental restorative materials may be excluded from the standard tensile testing of the dental restorative materials. For the flexural test, an arbitrary stress of 50 MPa was chosen for the composite resins and dental amalgams. However for the flexural strength of dental cements, the values of stress predicted at 0.01 percent probability of failure for all the materials are small. For this reason, the flexural test for dental cement should be excluded from the standard tensile testing of the dental restorative materials. If the test at the arbitrary stress fails, it is necessary for that the tester reviews the quality of the specimens and another 5 specimens should be tested. The data from the first and the second batch should be mutually analysed. If this set of specimens fails, it is suggested that a total of 30 specimens should be tested and a full Weibull analysis should be carried out.

CHAPTER TEN

PRINCIPLE FINDING

1. Weibull statistics is a better distribution equation to be used for analysing the strength of the brittle material. Weibull modulus and characteristic strength are their important parameters. The prediction at a lower and higher levels of failure probability are better than Normal statistics. Normal statistics gives an under-estimated stress at both extreme ends of failure probability.

2. The Normal statistics parameters (i.e mean strength and deviation coefficient(%)) of the large sample correlated well with the Weibull statistics parameters (i.e Weibull modulus and characteristic strength). Relationships between Weibull parameters and Normal parameters are found. These equations are proved useful when predicting the Weibull modulus and characteristic strength from the mean strength and deviation coefficient(%) of a small sample.

3. It was found that a crosshead speed of 0.1 mm per minute gave a reliable results for the compressive test when a specimens of diameter/depth ratio of 2:3 were used. The optimum specimen size is 4 mm diameter by 6 mm depth.

4. It was found that a crosshead speed of 0.5 mm per minute gave a reliable results for the diametral tensile test when a specimens of diameter/depth ration of 4:3 were used. The optimum specimen size is 4 mm diameter by 3 mm depth.

5. It was found that a crosshead speed of 0.5 mm per minute gave a reliable results for the flexural test when a specimens of span/depth ratio ranged from 5:1 to 10:1 were used.

6. Storage conditions where the specimens were stored before testing may affect the strength of some restorative materials. For example the compressive strength of Dispersalloy becomes less and it becomes more brittle when subjected to the moisture contamination. Therefore in-vitro testing should as close as possible simulate the condition in-vivo.

7. The value of the Weibull modulus may be related to the brittleness of the material. Weibull modulus is a measured of scatter of the data. A wide scatter of data is shown by a low value of Weibull modulus and vice-versa. The degree of brittleness increases as the value of Weibull modulus decreases.

8. Most brittle materials fails below the mean strength. By using Weibull statistics, performance of materials can be compared. This is carried out by calculating the stress at a low level of failure probability. The stresses at a low level of failure probability were reliably predict by the Weibull statistics.

9. An arbitrary stress at 0.01% failure probability was found to be the most reliable parameter to assess the strength of brittle materials. The stress predicted by Normal statistics at this failure probability level was under-estimated. The other strength parameters are Weibull modulus and characteristic strength.

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LIST OF APPENDICES

APPENDIX A

Strength Analysis Program Listing.

a. Weibull Strength Analysis for a Large Specimen Size.

```
 PROGRAM STRENGTHANALYSIS

REAL STRESS(1000),PROB(1000),SRANK(1000),XX(1000)
REAL TSUM1(1000),TSUM2(1000),ESTRES(1000),X(1000)
REAL PRO(3),GSUM(1000),WEIBC(1000),STRE(1000)
REAL STUD(3),NORMA(3),ISTRES

CHARACTER*40 TEST,MAT,ANSWER

COMMON /GRUP1/NUMDAT,STRESS,PROB,PROBB,SRANK
COMMON /GRUP2/LINK,XX,TALLY,STUD,NORMA
COMMON /GRUP3/STOTAL,SMEAN,SERROR,SVARIAN,STDDEV,COEFF
COMMON /GRUP4/CORREL,STDERR,WEIBULL,PRO,ESTRES
COMMON /GRUP5/MAT,TEST

PRINT*,'WHAT IS THE NAME OF THE MATERIAL TESTED ? '
PRINT*
PRINT*
READ(5,'(A)')MAT
PRINT*
PRINT*,'THE MECHANICAL TEST DONE, ENTER  '
PRINT*
PRINT*,'          COMPRESSIVE  '
PRINT*,'      OR'
PRINT*,'          DIAMETRAL  '
PRINT*,'      OR'
PRINT*,'          FLEXURAL  '
PRINT*
PRINT*
READ(5,'(A)')TEST
CALL DATAENTRY()

LINK=20
PRO(1)=0.0001
PRO(2)=0.01
PRO(3)=0.9999

CALL XSORT()
CALL XNORMAL()
CALL DWEIBUL(ISTRES)
CALL RESULY(ISTRES)

END
```

```
      SUBROUTINE DATA()
      COMMON /GRUP1/NUMDAT,STRESS,PROB,PROBB,SRANK
      REAL STRESS(1000),SRANK(1000),PROB(1000)
C     *****************************************
C     READ DATA SUBROUTINE
C     *****************************************
      PRINT*,'ENTER NO. OF DATA POINTS (N) ?'
      READ*,NUMDAT
      PRINT*,'ENTER THE DATA POINTS'
      PRINT*
      PRINT*
      DO 10 I=1,NUMDAT
      READ*,STRESS(I)
   10 CONTINUE
      END


      SUBROUTINE DATAFILE()
      COMMON /GRUP1/NUMDAT,STRESS,PROB,PROBB,SRANK
      COMMON /GRUP2/LINK,XX,TALLY,STUD,NORMA
C   ****************************************************
C     OPEN DATAFILE SUBROUTINE
C   ****************************************************
      INTEGER LINK
C      CHARACTER*40 FILNAM
C      CHARACTER*8 XSTAT
      INTEGER ERRCOD
C      PRINT*,'NAME OF FILE TO OPEN?'
C      READ(5,'(A)')FILNAM
C      PRINT*,'STATUS OF FILE: NEW OR OLD?'
C      READ(5,'(A)')XSTAT

      OPEN(UNIT=LINK,FILE='WEIBULL.DAT',STATUS='OLD',ACCESS=
     &'SEQUENTIAL',FORM='FORMATTED',IOSTAT=ERRCOD)
      IF(ERRCOD.EQ.0) THEN
      PRINT*,'DATAFILE SUCCESSFULLY OPENED'
      ELSE
      PRINT*,'CANNOT OPEN DATAFILE'
      END IF
      END


      SUBROUTINE RESULT()
      COMMON /GRUP1/NUMDAT,STRESS,PROB,PROBB,SRANK
      COMMON /GRUP2/LINK,XX,TALLY,STUD,NORMA
C   ****************************************************
C     WRITE RESULT TO FILE - RESULT SUBROUTINE
C   ****************************************************
      INTEGER LINK
C      CHARACTER*40 FILNAM
C      CHARACTER*8 XSTAT
      INTEGER ERRCOD
C      PRINT*,'NAME OF FILE TO OPEN?'
C      READ(5,'(A)')FILNAM
C      PRINT*,'STATUS OF FILE: NEW OR OLD?'
C      READ(5,'(A)')XSTAT
```

```
      OPEN(UNIT=LINK,FILE='WEIBULL.RES',STATUS='OLD',ACCESS=
     &'SEQUENTIAL',FORM='FORMATTED',IOSTAT=ERRCOD)
      IF(ERRCOD.EQ.0) THEN
      PRINT*,'RESULT SUCCESSFULLY WRITTEN'
      ELSE
      PRINT*,'ERROR-RESULT FILE CANNOT OPEN'
      END IF
      END

      SUBROUTINE DATAENTRY()
      COMMON /GRUP1/NUMDAT,STRESS,PROB,PROBB,SRANK
      COMMON /GRUP2/LINK,XX,TALLY,STUD,NORMA

C     ***************************************************
C     DATA ENTRY ROUTINE
C     ***************************************************
      REAL STRESS(1000)
      INTEGER  LINK

      CALL DATAFILE()

C      READ(LINK,*)NUMDAT
C      DO 10 I=1,NUMDAT
C      READ(LINK,*) STRESS(I)
C   10 CONTINUE
      L=1
   10 READ(LINK,*,END=30)STRESS(L)
      L=L+1
      GOTO 10
   30 NUMDAT=L-1
      PRINT*,'DATA ENTRY COMPLETE'
      CLOSE(UNIT=LINK)
C     ***************************************************
      END



      SUBROUTINE DWEIBUL(ISTRES)
      COMMON /GRUP1/NUMDAT,STRESS,PROB,PROBB,SRANK
      COMMON /GRUP3/STOTAL,SMEAN,SERROR,SVARIAN,STDDEV,COEFF
      COMMON /GRUP4/CORREL,STDERR,WEIBULL,PRO,ESTRES
C     ******************************************
C     SUBROUTINE TO CALCULATE WEIBULL PARAMETERS
C     ******************************************
      REAL PROB(1000),TSUMX(1000),TSUMY(1000)
      REAL PRO(3),ESTRES(1000),STRESS(1000)
      REAL GSUM1,GSUM2,GSUM3,GSUM4,GSUM5,GSUM6,STOTAL,SMEAN
      REAL WEIBULL,STD1,STD2,STDERR,CORREL,ISTRES
      REAL STRESO,MSTRES,COEFF,SVARIAN,SERROR,STDDEV
      REAL FSTRE1,FSTRE2,FSTRE3,GSUM7,GSUM8,GSUM9,ZSTRES

      VALUE=0
      ANUM=NUMDAT
      STRESO=VALUE
```

```
      GSUM1=VALUE
      GSUM2=VALUE
      GSUM3=VALUE
      GSUM4=VALUE
      GSUM5=VALUE
      GSUM6=VALUE
      GSUM7=VALUE
      GSUM8=VALUE

      DO 100 M=1,NSIZE
      TSUMX(M)=VALUE
      TSUMY(M)=VALUE
  100 CONTINUE


      DO 10 I=1,NUMDAT
      TSUMX(I)=LOG(LOG((1/(1-PROB(I)))))
      TSUMY(I)=LOG(STRESS(I)-STRESO)
   10 CONTINUE

      DO 20 I=1,NUMDAT
      GSUM1=GSUM1+TSUMY(I)
      GSUM2=GSUM2+TSUMX(I)
      GSUM3=GSUM3+(TSUMY(I)*TSUMY(I))
      GSUM4=GSUM4+(TSUMX(I)*TSUMX(I))
      GSUM5=GSUM5+(TSUMX(I)*TSUMY(I))
   20 CONTINUE

      GSUM6=GSUM5-(GSUM1*GSUM2/ANUM)
      GSUM7=GSUM3-(GSUM1*GSUM1/ANUM)
      GSUM8=GSUM4-(GSUM2*GSUM2/ANUM)

      WEIBULL=GSUM6/GSUM7

      STD1=(GSUM8-WEIBULL*GSUM6)/(ANUM-2)
      STD2=GSUM7
      STDERR=SQRT(STD1/STD2)

      CORE1=((GSUM2-(WEIBULL*GSUM1))/ANUM)*GSUM2
      CORE2=(GSUM5*WEIBULL)-(GSUM2*GSUM2)/ANUM
      CORREL=(CORE1+CORE2)/GSUM8

      ISTRES=EXP(-(((GSUM2-WEIBULL*GSUM1)/ANUM)/WEIBULL))

      DO 40 L=1,3
      FSTRE1=1/(1-PRO(L))
      FSTRE1=LOG(LOG(FSTRE1))
      FSTRE2=WEIBULL*LOG(ISTRES)
      FSTRE3=FSTRE1+FSTRE2
      FSTRE3=FSTRE3/WEIBULL
      ESTRES(L)= EXP(FSTRE3)

   40 CONTINUE

      END
```

```
      SUBROUTINE RESULY(ISTRES)
      COMMON /GRUP1/NUMDAT,STRESS,PROB,PROBB,SRANK
      COMMON /GRUP2/LINK,XX,TALLY,STUD,NORMA
      COMMON /GRUP3/STOTAL,SMEAN,SERROR,SVARIAN,STDDEV,COEFF
      COMMON /GRUP4/CORREL,STDERR,WEIBULL,PRO,ESTRES
      COMMON /GRUP5/MAT,TEST
C     ******************************************
C     SUBROUTINE TO PRINT A RESULT TO A FILE
C                 PART TWO
C     ******************************************
      REAL STRESS(1000),PROB(1000),SRANK(1000)
      REAL STUD(3),NORMA(3),PRO(3),ESTRES(3),ISTRES
      REAL WEIBULL,CORREL,STDERR,SMEAN,COEFF

      CHARACTER*40 TEST,MAT

      CALL RESULT()
      WRITE(LINK,10)
   10 FORMAT(T25,'STRENGTH ANALYSIS',/,/)
      WRITE(LINK,20)MAT
   20 FORMAT(T10,'TESTED MATERIAL          = ',A20)
      WRITE(LINK,30)TEST
   30 FORMAT(/,T10,'TYPE OF TEST             = ',A20)
      WRITE(LINK,40)NUMDAT
   40 FORMAT(/,T10,'NUMBER OF SPECIMEN       = ',I4.1)
C      WRITE(LINK,50)
C   50 FORMAT(/,/T10,'STRENGTH',T25,'RANK',T36,'PROBABILITY')
C      DO 70 K=1,NUMDAT
C      WRITE(LINK,60)STRESS(K),SRANK(K),PROB(K)
C   60 FORMAT(T10,F6.2,T23,F6.2,T38,F6.4)
C   70 CONTINUE
      WRITE(LINK,70)WEIBULL
   70 FORMAT(/,T10,'WEIBULL MODULUS           = ',F6.2,/)
      WRITE(LINK,80)CORREL
   80 FORMAT(T10,'CORRELATION COEFF       = ',F6.2,/)
      WRITE(LINK,90)STDERR
   90 FORMAT(T10,'STD ERROR OF MODULUS    = ',F6.4,/)
      WRITE(LINK,100)ISTRES
  100 FORMAT(T10,'CHARACTERISTIC STRENGTH = ',F6.2,/)
      WRITE(LINK,110)
  110 FORMAT(/T10,'PROBABILITY',T30,'CAL. STRENGTH')
      DO 130 K=1,3
      WRITE(LINK,120)PRO(K),ESTRES(K)
  120 FORMAT(/,T10,F8.4,T30,F8.2)
  130 CONTINUE
      WRITE(LINK,140)SMEAN
  140 FORMAT(/,/,T10,'MEAN STRENGTH               = ',F6.2,/)
      WRITE(LINK,150)COEFF
  150 FORMAT(T10,'DEVIATION COEFFICIENT   = ',F6.2,/)
      WRITE(LINK,160)
  160 FORMAT(/T10,'PROBABILITY',T30,'NORMAL-CAL. STRENGTH')
      DO 180 K=1,3
      WRITE(LINK,170)PRO(K),NORMA(K)
  170 FORMAT(/,T10,F8.4,T33,F8.2)
  180 CONTINUE
      WRITE(LINK,190)
  190 FORMAT(/,/,T10,'PROBABILITY',T30,'STUDENT-CAL. STRENGTH')
```

```
      DO 200 J=1,3
      WRITE(LINK,210)PRO(J),STUD(J)
  210 FORMAT(/,T10,F8.4,T33,F8.2)
  200 CONTINUE

      CLOSE(LINK)

      END


      SUBROUTINE XSORT()
      COMMON /GRUP1/NUMDAT,STRESS,PROB,PROBB,SRANK
      COMMON /GRUP2/LINK,XX,TALLY,STUB,NORMA

C     ******************************************
C     SUBROUTINE TO XSORT THE DATA
C     ******************************************
      REAL STRESS(1000),X(1000),XX(1000),SRANK(1000),PROB(1000)
      REAL Z,Y,TALLY,BTALLY

      ANUM=NUMDAT
      TALLY=0

      DO 20 I=1,(NUMDAT-1)
      DO 10 J=1,(NUMDAT-1)
      Z=STRESS(J)
      Y=STRESS(J+1)
      IF(Z.LE.Y) THEN
      GOTO 10
      ELSE
      STRESS(J)=Y
      STRESS(J+1)=Z
      ENDIF
   10 CONTINUE
   20 CONTINUE


      DO 30 J=1,NUMDAT
      IF (STRESS(J) .NE. STRESS(J+1) .AND.
     &STRESS(J) .NE. STRESS(J-1)) THEN
      SRANK(J)=J
      ELSE IF (STRESS(J) .EQ. STRESS(J+1)) THEN
      TALLY= TALLY+1
      ELSE IF (STRESS(J) .EQ. STRESS(J+2)) THEN
      GOTO 70
      ELSE IF (TALLY .EQ. 1) THEN
      BTALLY=0
      BTALLY=((J+(J+TALLY))/2)-1
      DO 40 L=(J-1),J
      SRANK(L)=BTALLY
   40 CONTINUE
      TALLY=0

      ELSE IF (TALLY .GT.1 ) THEN
      BTALLY=0
      ITALLY=TALLY-1
```

```
      JTALLY=TALLY+1
      DO 50 N=(J-ITALLY),(J+1)
      BTALLY=BTALLY+N
   50 CONTINUE
      DO 80 M=(J-ITALLY),J
      SRANK(M)=(BTALLY/JTALLY)-1
   80 CONTINUE
      TALLY=0
   70 END IF

   30 CONTINUE

      DO 90 I=1,NUMDAT
      IF (SRANK(I) .EQ. 0) THEN
      SRANK(I)=SRANK(I+1)
      END IF
   90 CONTINUE

      DO 100 J=1,NUMDAT
      PROB(J)=SRANK(J)/(NUMDAT+1)
  100 CONTINUE

      END



      SUBROUTINE XNORMAL()
      COMMON /GRUP1/NUMDAT,STRESS,PROB,PROBB,SRANK
      COMMON /GRUP2/LINK,XX,TALLY,STUD,NORMA
      COMMON /GRUP3/STOTAL,SMEAN,SERROR,SVARIAN,STDDEV,COEFF

C     ********************************************
C     SUBROUTINE TO XSORT THE DATA
C     ********************************************
      REAL STRESS(1000),STUD(3),NORMA(3)
      REAL STDDEV,COEFF

      ANUM=NUMDAT

      DO 50 I=1,3
      NORMA(I)=0
      STUD(I)=0
   50 CONTINUE

      STOTAL=0
      DO 10 J=1,NUMDAT
      STOTAL=STRESS(J)+STOTAL
   10 CONTINUE

      SMEAN=STOTAL/ANUM

      SERROR=0
      DO 20 K=1,NUMDAT
      SERROR=((STRESS(K)-SMEAN)**2)+SERROR
   20 CONTINUE
```

```
SVARIAN=SERROR/ANUM
STDDEV=SQRT(SVARIAN)
COEFF=(STDDEV/SMEAN)*100


NORMA(1)=SMEAN-((STDDEV*3.7)/(SQRT(ANUM)))
NORMA(2)=SMEAN-((STDDEV*2.33)/(SQRT(ANUM)))
NORMA(3)=SMEAN+((STDDEV*3.7)/(SQRT(ANUM)))
STUD(1)=SMEAN-((STDDEV*4.411)/(SQRT(ANUM)))
STUD(2)=SMEAN-((STDDEV*2.462)/(SQRT(ANUM)))
STUD(3)=SMEAN+((STDDEV*4.411)/(SQRT(ANUM)))

END
```

b. A Program to Predict a stress at 0.01%, 0.1%, 1% and 99.99% probability of failure by using a mean strength and deviation coefficient of a small sample (5 specimens).

```
      PROGRAM STRESSPREDICT

      REAL STDDEV,SMEAN,PRO(4),NORMA(4),STUD(4),COEFF
      INTEGER ERRCOD

      LINK=20
      ANUM=5
      PRO(1)=0.01
      PRO(2)=0.1
      PRO(3)=1.0
      PRO(4)=99.99

      PRINT*,'ENTER MEAN STRENGTH = '
      READ*,SMEAN
      PRINT*,'ENTER DEVIATION COEFFICIENT(%) = '
      READ*,COEFF

      STDDEV=(COEFF*SMEAN)/100
      WEIBULL=EXP(-(LN(COEFF/99.2))/0.973)
      ISTRES= SMEAN/(0.995-0.04*COEFF)

      NORMA(1)=SMEAN-(STDDEV*3.7)/SQRT(ANUM)
      NORMA(2)=SMEAN-(STDDEV*3.09)/SQRT(ANUM)
      NORMA(3)=SMEAN-(STDDEV*2.33)/SQRT(ANUM)
      NORMA(4)=SMEAN+(STDDEV*3.7)/SQRT(ANUM)

      STUD(1)=SMEAN-((STDDEV*14.773)/SQRT(ANUM))
      STUD(2)=SMEAN-((STDDEV*7.173)/SQRT(ANUM))
      STUD(3)=SMEAN-((STDDEV*3.747)/SQRT(ANUM))
      STUD(4)=SMEAN+((STDDEV*14.773)/SQRT(ANUM))

      DO 10 L=1,4
      FSTRE1=1/(1-PRO(L))
      FSTRE1=LOG(LOG(FSTRE1))
      FSTRE2=WEIBULL*LOG(ISTRES)
      FSTRE3=FSTRE1+FSTRE2
      FSTRE3=FSTRE3/WEIBULL
      ESTRES(L)= EXP(FSTRE3)

   10 CONTINUE
```

```
      OPEN(UNIT=LINK,FILE='PREDICT5.RES',STATUS='OLD',ACCESS=
     &'SEQUENTIAL',FORM='FORMATTED',IOSTAT=ERRCOD)
      IF(ERRCOD.EQ.0) THEN
      PRINT*,'RESULT SUCCESSFULLY WRITTEN TO PREDICT5.RES'
      ELSE
      PRINT*,'ERROR-RESULT FILE CANNOT OPEN'
      END IF

      WRITE(LINK,600)
  600 FORMAT(T25,'STRESS PREDICTION',/,/)
      WRITE(LINK,110)
      WRITE(LINK,140)SMEAN
  140 FORMAT(/,/,T10,'MEAN STRENGTH                = ',F6.2,/)
      WRITE(LINK,150)COEFF
  150 FORMAT(T10,'DEVIATION COEFFICIENT   = ',F6.2,/)
      WRITE(LINK,70)WEIBULL
   70 FORMAT(/,T10,'WEIBULL MODULUS              = ',F6.2,/)
      WRITE(LINK,100)ISTRES
  100 FORMAT(T10,'CHARACTERISTIC STRENGTH = ',F6.2,/)
  110 FORMAT(/T10,'PROBABILITY',T30,'WEIBULL-CAL. STRENGTH')
      DO 120 K=1,4
      WRITE(LINK,130)PRO(K),ESTRESS(K)
  130 FORMAT(/,T10,F8.4,T33,F8.2)
  120 CONTINUE
      WRITE(LINK,160)
  160 FORMAT(/T10,'PROBABILITY',T30,'NORMAL-CAL. STRENGTH'0
      DO 180 K=1,4
      WRITE(LINK,170)PRO(K),NORMA(K)
  170 FORMAT(/,T10,F8.4,T33,F8.2)
  180 CONTINUE
      WRITE(LINK,190)
  190 FORMAT(/,/,T10,'PROBABILITY',T30,'STUDENT-CAL. STRENGTH')
      DO 200 J=1,4
      WRITE(LINK,210)PRO(J),STUD(J)
  210 FORMAT(/,T10,F8.4,T33,F8.2)
  200 CONTINUE

      CLOSE(LINK)


      END
```

APPENDIX B

1. Typical Output of the Strength Analysis - Program (a).

STRENGTH ANALYSIS

TESTED MATERIAL	= Occlusin
TYPE OF TEST	= Compressive test(1 hr)
NUMBER OF SPECIMEN	= 30
WEIBULL MODULUS	= 16.9
CORRELATION COEFF	= 0.93
STD ERROR OF MODULUS	= 0.87
CHARACTERISTIC STRENGTH	= 168.6

PROBABILITY	CAL. STRENGTH
0.0001	97.8
0.0100	128.4
0.9999	184.6

MEAN STRENGTH	= 163.7
DEVIATION COEFFICIENT	= 6.4

PROBABILITY	NORMAL-CAL. STRENGTH
0.0001	156.6
0.0100	159.3
0.9999	170.7

PROBABILITY	STUDENT-CAL. STRENGTH
0.0001	155.26
0.0100	158.64
0.9999	172.14

2. Typical Output of the Strength Analysis - Program (b).

STRESS PREDICTION

MEAN STRENGTH	= 117.4
DEVIATION COEFFICIENT	= 13.8
WEIBULL MODULUS	= 7.6
CHARACTERISTIC STRENGTH	= 125.2

PROBABILITY	WEIBULL-CAL. STRENGTH
0.0100	37.26
0.1000	50.45
1.0000	68.35
99.9900	167.80

PROBABILITY	NORMAL-CAL. STRENGTH
0.0100	90.59
0.1000	95.01
1.0000	100.50
99.9900	144.21

PROBABILITY	STUDENT-CAL. STRENGTH
0.0100	10.36
0.1000	65.43
1.0000	90.25
99.9900	224.43

3. Sample Calculations for Program (a).

3.1 To calculate the stress at probability of failure for the Normal Statistic.

i. Normal Distribution.

For the probability of less than 0.5

$$\text{Stress} = \text{Mean strength} - \frac{\text{Standard deviation} * \text{Normal Deviate}}{\text{Square-root(Number of data)}}$$

or for the probability of greater than 0.5

$$\text{Stress} = \text{Mean strength} + \frac{\text{Standard deviation} * \text{Normal Deviate}}{\text{Square-root(Number of data)}}$$

$$\text{Where Std deviation} = \frac{\text{Mean Strength} * \text{Deviation Coeff.(\%)}}{100}$$

and Normal deviate is the taken form Table 1 of the appendix D. For example, for the probablility ($P_{(x)}$) of 0.0001 (0.01 precent), the Normal deviate is equal to 3.7. This deviate is the same for the probability of 0.9999 (99.99 percent). The Normal deviate for the probability of 0.01 (1 precent) is equal to 2.33

Example: The stress at 1 precent failure probability for the program output above where the mean strength equal to 163.7 Mpa and deviation coefficient is equal to 6.4 (Appendix B(1)). Number of specimen is 30 (Appendix B(2)).

$$\text{Stress at 1\% failure prob.} = 163.7 - \frac{((163.7*6.4)/100)*2.33}{\text{Sq-root(30)}}$$

$$= \underline{159.28 \text{ Mpa}}.$$

ii. Student Distribution.

For the probability of less than 0.5

$$\text{Stress} = \text{Mean strength} - \frac{\text{Standard deviation} * \text{Student Deviate}}{\text{Square-root(Number of data)}}$$

or for the probability of greater than 0.5

$$\text{Stress} = \text{Mean strength} + \frac{\text{Standard deviation} * \text{Student Deviate}}{\text{Square-root(Number of data)}}$$

$$\text{Where Std deviation} = \frac{\text{Mean Strength} * \text{Deviation Coeff.(\%)}}{100}$$

and Student deviate is the taken form Table 2 of the appendix D. For example, for the probablility ($P_{(x)}$) of 0.0001 (0.01 percent) for 30 data, the Student deviate is equal to 4.411(29 degree of freedom). This deviate is the same for the probability of 0.9999 (99.99 percent). The Student deviate for the probability of 0.01 (1 precent) is equal to 2.462 .

Example: The stress at 1 precent failure probability for the program output above where the mean strength equal to 163.7 Mpa and devuation coefficient is equal to 6.4 Number of specimen is 30 (Appendix B(1)).

$$\text{Stress at 1\% failure prob.} = 163.7 - \frac{(163.7*6.4)*2.462}{\text{Sq-root}(30)*100}$$

$$= \underline{158.64 \text{ Mpa}}.$$

4. Sample Calculations for Program (b).

4.1 To calculate the stress at probability of failure for the Normal Statistic.

i. Normal Distribution.

For the probability of less than 0.5

$$\text{Stress} = \text{Mean strength} - \frac{\text{Standard deviation} * \text{Normal Deviate}}{\text{Square-root(Number of data)}}$$

or for the probability of greater than 0.5

$$\text{Stress} = \text{Mean strength} + \frac{\text{Standard deviation} * \text{Normal Deviate}}{\text{Square-root(Number of data)}}$$

$$\text{Where Std deviation} = \frac{\text{Mean Strength} * \text{Deviation Coeff.(\%)}}{100}$$

and Normal deviate is the taken form Table 1 of the appendix D. For example, for the probablility ($P_{(x)}$) of 0.0001 (0.01 precent), the Normal deviate is equal to 3.7. This deviate is the same for the probability of 0.9999 (99.99 percent). The Normal deviate for the probability of 0.01 (1 precent) is equal to 2.33

Example: The stress at 1 precent failure probability for the program output above where the mean strength equal to 117.4 Mpa and deviation coefficient is equal to 13.8 (Appendix B(2)).Number of specimen is 5 (Appendix B(2)).

$$\text{Stress at 1\% failure prob.} = 117.4 - \frac{((117.4*13.8)/100)*2.33}{\text{Sq-root}(5)}$$

$$= \underline{100.5 \text{ Mpa}}.$$

ii. Student Distribution.

For the probability of less than 0.5

$$\text{Stress} = \text{Mean strength} - \frac{\text{Standard deviation} * \text{Student Deviate}}{\text{Square-root(Number of data)}}$$

or for the probability of greater than 0.5

$$\text{Stress} = \text{Mean strength} + \frac{\text{Standard deviation} * \text{Student Deviate}}{\text{Square-root(Number of data)}}$$

$$\text{Where Std deviation} = \frac{\text{Mean Strength} * \text{Deviation Coeff.(\%)}}{100}$$

and Student deviate is the taken form Table 2 of the appendix D. For example, for the probablility ($P_{(x)}$) of 0.0001 (0.01 percent) for 5 data, the Student deviate is equal to 14.773(4 degree of freedom). This deviate is the same for the probability of 0.9999 (99.99 percent). The Student deviate for the probability of 0.01 (1 precent) is equal to 3.747 .

Example: The stress at 1 precent failure probability for the program output above where the mean strength equal to 117.4 Mpa and devuation coefficient is equal to 13.8. Number of specimen is 5 (Appendix B(2)).

$$\text{Stress at 1\% failure prob.} = 117.4 - \frac{(117.4*13.8)*3.747}{\text{Sq-root}(5)*100}$$

$$= \underline{90.25 \text{ Mpa}}.$$

APPENDIX C

1. Materials

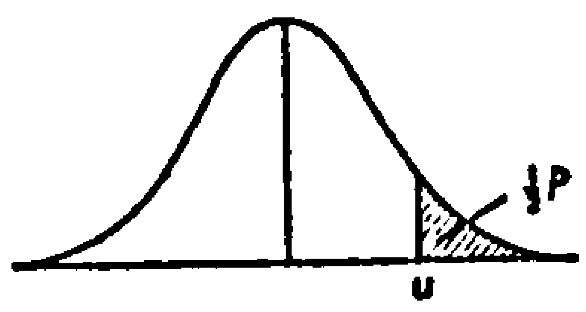
a. Amalcap	Vivadent, schaan, Lichtenstein.
b. Dispersalloy	Johnson and Johnson Dental Products Company East Windsor N.J 08520.
c. Occlusin	Imperial Chemical Industries Plc Hulley Road, Macclesfield Cheshire, England.
d. Opalux	Imperial Chemical Industries Plc Hulley Road, Macclesfield Cheshire, England.
e. P50	Dental Products Division/3M St. Paul MN 5514
f. Silux	Dental Products Division/3M St. Paul MN 5514
g. Ketac-Fil	Espa Fabrik Pharmazeutischer Praparate Gmbh & Co. Kg D-8031 Seefeld/Oberbay Germany.
h. Ketac-Silver	Espa Fabrik Pharmazeutischer Praparate Gmbh & Co. Kg D-8031 Seefeld/Oberbay Germany.
i. Plaster of Paris	British Gypsum Industrial Product Division Newark On Trent, U.K

APPENDIX D

Table 1 - Standardised Normal Deviates.

AREAS IN TAIL OF THE NORMAL DISTRIBUTION

Single-tail areas in terms of standardized deviates



The function tabulated is ½*P*, the probability of obtaining a standardized normal deviate greater than *u*, *in one direction*. The two-tail probability, *P*, is twice the tabulated value.

u	0·00	0·01	0·02	0·03	0·04	0·05	0·06	0·07	0·08	0·09
0·0	0·5000	0·4960	0·4920	0·4880	0·4840	0·4801	0·4761	0·4721	0·4681	0·4641
0·1	0·4602	0·4562	0·4522	0·4483	0·4443	0·4404	0·4364	0·4325	0·4286	0·4247
0·2	0·4207	0·4168	0·4129	0·4090	0·4052	0·4013	0·3974	0·3936	0·3897	0·3859
0·3	0·3821	0·3783	0·3745	0·3707	0·3669	0·3632	0·3594	0·3557	0·3520	0·3483
0·4	0·3446	0·3409	0·3372	0·3336	0·3300	0·3264	0·3228	0·3192	0·3156	0·3121
0·5	0·3085	0·3050	0·3015	0·2981	0·2946	0·2912	0·2877	0·2843	0·2810	0·2776
0·6	0·2743	0·2709	0·2676	0·2643	0·2611	0·2578	0·2546	0·2514	0·2483	0·2451
0·7	0·2420	0·2389	0·2358	0·2327	0·2296	0·2266	0·2236	0·2206	0·2177	0·2148
0·8	0·2119	0·2090	0·2061	0·2033	0·2005	0·1977	0·1949	0·1922	0·1894	0·1867
0·9	0·1841	0·1814	0·1788	0·1762	0·1736	0·1711	0·1685	0·1660	0·1635	0·1611
1·0	0·1587	0·1562	0·1539	0·1515	0·1492	0·1469	0·1446	0·1423	0·1401	0·1379
1·1	0·1357	0·1335	0·1314	0·1292	0·1271	0·1251	0·1230	0·1210	0·1190	0·1170
1·2	0·1151	0·1131	0·1112	0·1093	0·1075	0·1056	0·1038	0·1020	0·1003	0·0985
1·3	0·0968	0·0951	0·0934	0·0918	0·0901	0·0885	0·0869	0·0853	0·0838	0·0823
1·4	0·0808	0·0793	0·0778	0·0764	0·0749	0·0735	0·0721	0·0708	0·0694	0·0681
1·5	0·0668	0·0655	0·0643	0·0630	0·0618	0·0606	0·0594	0·0582	0·0571	0·0559
1·6	0·0548	0·0537	0·0526	0·0516	0·0505	0·0495	0·0485	0·0475	0·0465	0·0455
1·7	0·0446	0·0436	0·0427	0·0418	0·0409	0·0401	0·0392	0·0384	0·0375	0·0367
1·8	0·0359	0·0351	0·0344	0·0336	0·0329	0·0322	0·0314	0·0307	0·0301	0·0294
1·9	0·0287	0·0281	0·0274	0·0268	0·0262	0·0256	0·0250	0·0244	0·0239	0·0233
2·0	0·02275	0·02222	0·02169	0·02118	0·02068	0·02018	0·01970	0·01923	0·01876	0·01831
2·1	0·01786	0·01743	0·01700	0·01659	0·01618	0·01578	0·01539	0·01500	0·01463	0·01426
2·2	0·01390	0·01355	0·01321	0·01287	0·01255	0·01222	0·01191	0·01160	0·01130	0·01101
2·3	0·01072	0·01044	0·01017	0·00990	0·00964	0·00939	0·00914	0·00889	0·00866	0·00842
2·4	0·00820	0·00798	0·00776	0·00755	0·00734	0·00714	0·00695	0·00676	0·00657	0·00639
2·5	0·00621	0·00604	0·00587	0·00570	0·00554	0·00539	0·00523	0·00508	0·00494	0·00480
2·6	0·00466	0·00453	0·00440	0·00427	0·00415	0·00402	0·00391	0·00379	0·00368	0·00357
2·7	0·00347	0·00336	0·00326	0·00317	0·00307	0·00298	0·00289	0·00280	0·00272	0·00264
2·8	0·00256	0·00248	0·00240	0·00233	0·00226	0·00219	0·00212	0·00205	0·00199	0·00193
2·9	0·00187	0·00181	0·00175	0·00169	0·00164	0·00159	0·00154	0·00149	0·00144	0·00139
3·0	0·00135									
3·1	0·00097									
3·2	0·00069									
3·3	0·00048									
3·4	0·00034									
3·5	0·00023									
3·6	0·00016									
3·7	0·00011									
3·8	0·00007									
3·9	0·00005									
4·0	0·00003									

Standardized deviates in terms of two-tail areas

P	1·0	0·9	0·8	0·7	0·6	0·5	0·4
u	0	0·126	0·253	0·385	0·524	0·674	0·842
P	0·3	0·2	0·1	0·05	0·02	0·01	0·001
u	1·036	1·282	1·645	1·960	2·326	2·576	3·291

Table 2 - Standardised Student Deviates.

PERCENTAGE POINTS OF THE t-DISTRIBUTION—VALUES OF t IN TERMS OF A AND ν

$\nu \backslash A$	0.2	0.5	0.8	0.9	0.95	0.98	0.99	0.995	0.998	0.999	0.9999	0.99999	0.999999
1	0.325	1.000	3.078	6.314	12.706	31.821	63.657	127.321	318.309	636.619	6366.198	63661.977	636619.772
2	0.289	0.816	1.886	2.920	4.303	6.965	9.925	14.089	22.327	31.598	99.992	316.225	999.999
3	0.277	0.765	1.638	2.353	3.182	4.541	5.841	7.453	10.214	12.924	28.000	60.397	130.155
4	0.271	0.741	1.533	2.132	2.776	3.747	4.604	5.598	7.173	8.610	15.544	27.771	49.459
5	0.267	0.727	1.476	2.015	2.571	3.365	4.032	4.773	5.893	6.869	11.178	17.897	28.477
6	0.265	0.718	1.440	1.943	2.447	3.143	3.707	4.317	5.208	5.959	9.082	13.555	20.047
7	0.263	0.711	1.415	1.895	2.365	2.998	3.499	4.029	4.785	5.408	7.885	11.215	15.764
8	0.262	0.706	1.397	1.860	2.306	2.896	3.355	3.833	4.501	5.041	7.120	9.782	13.257
9	0.261	0.703	1.383	1.833	2.262	2.821	3.250	3.690	4.297	4.781	6.594	8.827	11.637
10	0.260	0.700	1.372	1.812	2.228	2.764	3.169	3.581	4.144	4.587	6.211	8.150	10.516
11	0.260	0.697	1.363	1.796	2.201	2.718	3.106	3.497	4.025	4.437	5.921	7.648	9.702
12	0.259	0.695	1.356	1.782	2.179	2.681	3.055	3.428	3.930	4.318	5.694	7.261	9.085
13	0.259	0.694	1.350	1.771	2.160	2.650	3.012	3.372	3.852	4.221	5.513	6.955	8.604
14	0.258	0.692	1.345	1.761	2.145	2.624	2.977	3.326	3.787	4.140	5.363	6.706	8.218
15	0.258	0.691	1.341	1.753	2.131	2.602	2.947	3.286	3.733	4.073	5.239	6.502	7.903
16	0.258	0.690	1.337	1.746	2.120	2.583	2.921	3.252	3.686	4.015	5.134	6.330	7.642
17	0.257	0.689	1.333	1.740	2.110	2.567	2.898	3.223	3.646	3.965	5.044	6.184	7.421
18	0.257	0.688	1.330	1.734	2.101	2.552	2.878	3.197	3.610	3.922	4.966	6.059	7.232
19	0.257	0.688	1.328	1.729	2.093	2.539	2.861	3.174	3.579	3.883	4.897	5.949	7.069
20	0.257	0.687	1.325	1.725	2.086	2.528	2.845	3.153	3.552	3.850	4.837	5.854	6.927
21	0.257	0.686	1.323	1.721	2.080	2.518	2.831	3.135	3.527	3.819	4.784	5.769	6.802
22	0.256	0.686	1.321	1.717	2.074	2.508	2.819	3.119	3.505	3.792	4.736	5.694	6.692
23	0.256	0.685	1.319	1.714	2.069	2.500	2.807	3.104	3.485	3.768	4.693	5.627	6.593
24	0.256	0.685	1.318	1.711	2.064	2.492	2.797	3.090	3.467	3.745	4.654	5.566	6.504
25	0.256	0.684	1.316	1.708	2.060	2.485	2.787	3.078	3.450	3.725	4.619	5.511	6.424
26	0.256	0.684	1.315	1.706	2.056	2.479	2.779	3.067	3.435	3.707	4.587	5.461	6.352
27	0.256	0.684	1.314	1.703	2.052	2.473	2.771	3.057	3.421	3.690	4.558	5.415	6.286
28	0.256	0.683	1.313	1.701	2.048	2.467	2.763	3.047	3.408	3.674	4.530	5.373	6.225
29	0.256	0.683	1.311	1.699	2.045	2.462	2.756	3.038	3.396	3.659	4.506	5.335	6.170
30	0.256	0.683	1.310	1.697	2.042	2.457	2.750	3.030	3.385	3.646	4.482	5.299	6.119
40	0.255	0.681	1.303	1.684	2.021	2.423	2.704	2.971	3.307	3.551	4.321	5.053	5.768
60	0.254	0.679	1.296	1.671	2.000	2.390	2.660	2.915	3.232	3.460	4.169	4.825	5.449
120	0.254	0.677	1.289	1.658	1.980	2.358	2.617	2.860	3.160	3.373	* 4.025	* 4.613	* 5.158
∞	0.253	0.674	1.282	1.645	1.960	2.326	2.576	2.807	3.090	3.291	3.891	4.417	4.892

$$A = A(t|\nu) = \left[\sqrt{\nu}\, B\left(\frac{1}{2}, \frac{\nu}{2}\right)\right]^{-1} \int_{-t}^{t} \left(1+\frac{x^2}{\nu}\right)^{-\left(\frac{\nu+1}{2}\right)} dx$$

From E. S. Pearson and H. O. Hartley (editors), Biometrika tables for statisticians, vol. I. Cambridge Univ. Press, Cambridge, England, 1954 for A 0.999, from E. T. Federighi, Extended tables of the percentage points of Student's t-distribution, J. Amer. Statist. Assoc. 54, 683-688 (1959) for A 0.999 (with permission).